CALIFORNIA INSTITUTE OF TECHNOLOGY

EARTHQUAKE ENGINEERING RESEARCH LABORATORY

# STATIC AND DYNAMIC TESTS OF A FULL-SCALE STEEL-FRAME STRUCTURE

by

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Pasadena, California

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## ABSTRACT

Basic experimental data are presented for four tests performed on a full-scale steel-frame building: (1) Static unloading test, involving strain-gage measurements on structural members loaded by the vertical dead weight of the structure, (2) Strain-gage measurements of temperature-induced strains during a 24-hour period, (3) Strain-gage measurement of static strains caused by a lateral force applied by a cable, and (4) Dynamic resonance tests in which the structure was excited laterally by sinusoidal force generators. In connection with the interpretation of these experiments, measurements were also made of ground and structure vibrations caused by an adjacent power generation plant.

# INTRODUCTION

The possibility of testing the Blair High School Gymnasium, Pasadena, California, was first suggested to Caltech by the design engineer, Paul Winter of Neptune & Thomas and Associates. Since the gymnasium roof was being constructed in a stress-free condition and the application of the dead load to the structure would produce stresses in the structural members of 60% or more of the total design load, Professors D. E. Hudson and C. W. McCormick, Jr. agreed that the structure and test opportunity was unique enough to justify an experimental investigation. It was decided that Caltech would undertake an experimental and theoretical analysis of the stresses in the members caused by the dead weight of the structure and that a dynamic study of the structure would also be made.

The number of strain gage locations desired to give a good representative view of the member stresses quickly grew in magnitude beyond the capability of the Caltech personnel and equipment to handle under the time limitation. It was seen that this project might be appropriate for application of an automatic strain-recording system coupled with a digital readout which could be used for rapid computer processing of the data. The Jet Propulsion Laboratory had used just such a system for their experimental studies of spacecraft structures. It was learned that JPL and NASA were interested in this project as a potentially valuable demonstration of the contribution which space-oriented research could make to modern engineering technology. It was decided that Caltech would provide the overall technical supervision of the project and that Caltech and JPL would take independent strain readings. This provided a cross-check on the two different reading and data-reducing systems.

The automatic data-recording system used by JPL provided an ideal way to extend the experimental investigation from the dead load-stress study to a twenty-four hour time-temperature-stress study of the gymnasium roof. As an additional check on structural properties, a horizontal static load experiment with a maximum horizontal force of 10, 000 pounds was made. It was felt that this study would also provide a connection between the member stresses and the dynamic response of the structure.

Experimental dynamic studies were also performed on the structure. The dynamic force was generated by one of the force generators developed at Caltech and owned by the State of California, Division of Architecture. The force generator was mounted three feet below the roof on the centerline of the structure. The motion of the structure was measured with accelerometers.

The present report is concerned primarily with the presentation of the data without analysis and interpretation. The instrumentation used in the experiments is described and the main features and details of the structure itself are also presented. The raw data from the dead load experiment, the time-temperature experiment, and the horizontal static load experiment are presented in engineering units. Further data treatment such as compensating for temperature effects have not been made at this time, since this will be a part of the final data analysis computer program. The dynamic data are presented as plotted frequency response curves of the structure.

The writer wishes to acknowledge the assistance in performing the experiments and preparing this report given by K. L. Heitner, L. D. Lutes, N. C. Nigam, R. D. Rocke, N.-C. T'sai (graduate students at Caltech), Dr. S. F. Masri (Research Fellow at Caltech), R. Ronderos, and R. J. Williams. Thanks are also given to M. Jessey and Dr. C. Babcock of the Aeronautics Department for the use of their strain gage switch box. Extra thanks are given to Dr. D. E. Hudson and Professor C. W. McCormick, Jr. who made this project possible.

We are much indebted to the staff of the Jet Propulsion Laboratory of the National Aeronautics and Space Administration for their great effort in carrying out the test work under pressure of a very restricted time schedule. The idea of the cooperative program grew out of discussions with Dr. S. J. Slomich and Dr. A. R. Hibbs. Operational aspects were carried out under the direction of C. M. Berdahl and K. C. Sutherland. The interest and assistance of the Director of the Laboratory, Dr. W. H. Pickering, and of the Assistant to the Director, Dr. B. P. Huber, is much appreciated.

The cooperation of the structural design engineer, Paul Winter of Neptune & Thomas and Associates, Harry Bozwell, job superintendent of the S. Patti Construction Company, general contractor, and of the Western Iron and Metal Company, structural steel subcontractor is sincerely appreciated. Thanks are also extended to the Pasadena School Board for the opportunity to test this structure.

## DESCRIPTION OF THE STRUCTURE

The gymnasium roof plan consists of four connecting circular arcs, with a major dimension of 151 feet and a minor dimension of 119 feet. The roof itself consists of ridge and valley steel plate members connected with sheet metal decking. This folded plate roof spans from the exterior pipe columns to a center truss. This center truss area is supported by the roof and is divided into three levels which house the ventilation system for the gymnasium. Figure 1 shows a plan of the roof with the ridge and valley lines numbered to assist in describing the location of the strain gages used in this study. The numbers on the roof indicate the locations of strain gages mounted on the metal decking. Figure 2 gives a composite cross section of the gymnasium. The structural members are identified with the exceptions of the sheet gage of the metal deck and the members of the center truss. The area within the center truss consisting of three floors will be called the equipment room for the purposes of this report.

Figure 3 is a photograph of the connection at the equipment room of the roof ridge member before final welding was accomplished. The photograph in Figure 4 shows the roof valley member connection to the equipment room. Note the concrete slab in the equipment room at the valley member connection level. Also the metal deck used to connect the ridge and valley members can be seen in Figures 3 and 4. A view of the gymnasium from the north is given in Figure 5. The exterior walls have been covered with a paper lath supported by metal channels preparatory to plastering.

The gymnasium roof was constructed in a stress-free condition with the total dead load to be applied to the structure after completion of the structural frame. The concrete floor slab directly below the equipment room was placed before roof construction began. This concrete floor formed the base of the falsework on which the equipment room was constructed in place. The ridge and valley members also were supported along their lengths until the metal deck was placed and the entire structure welded.

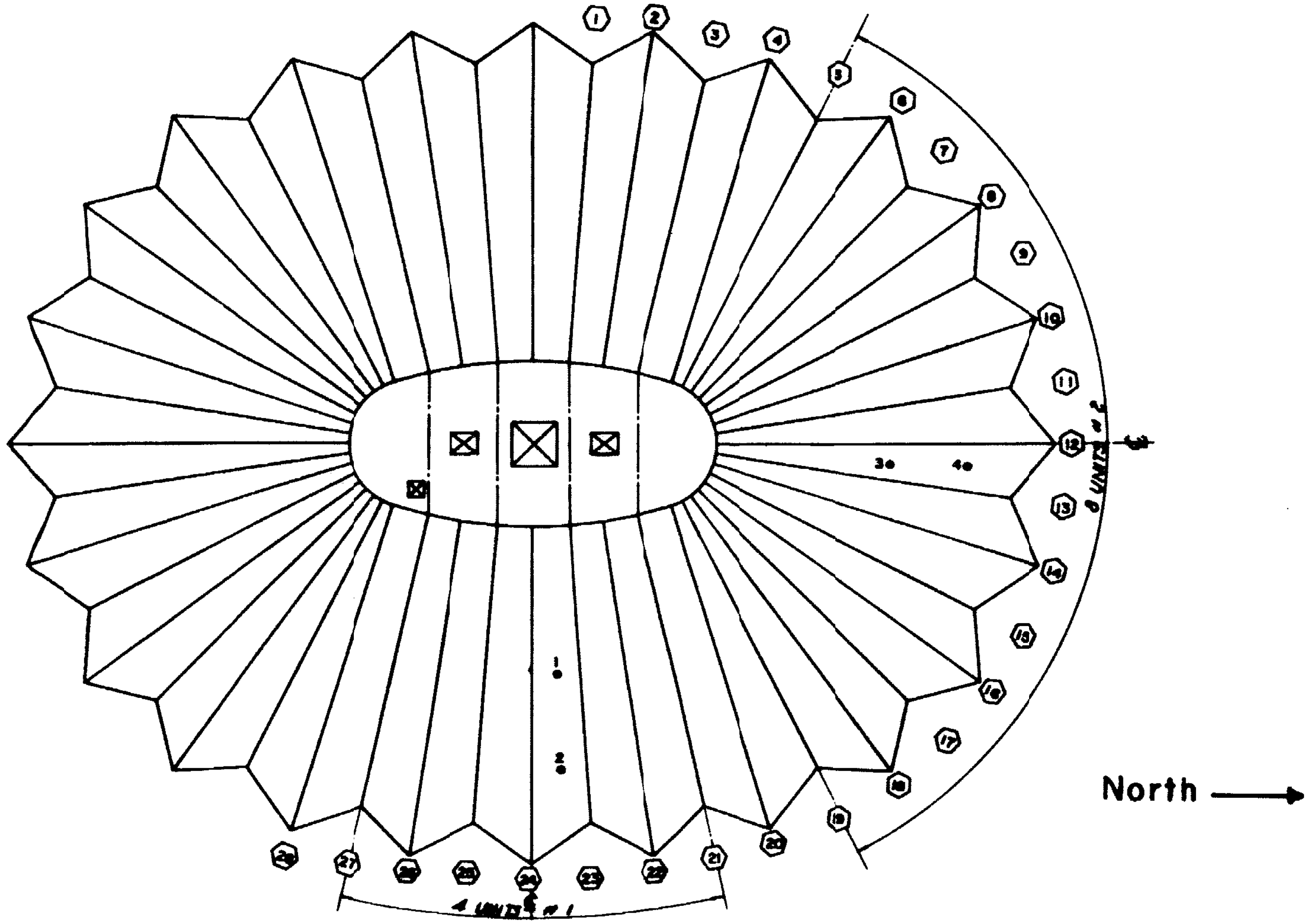



Fig. 1. Gymnasium roof plan.

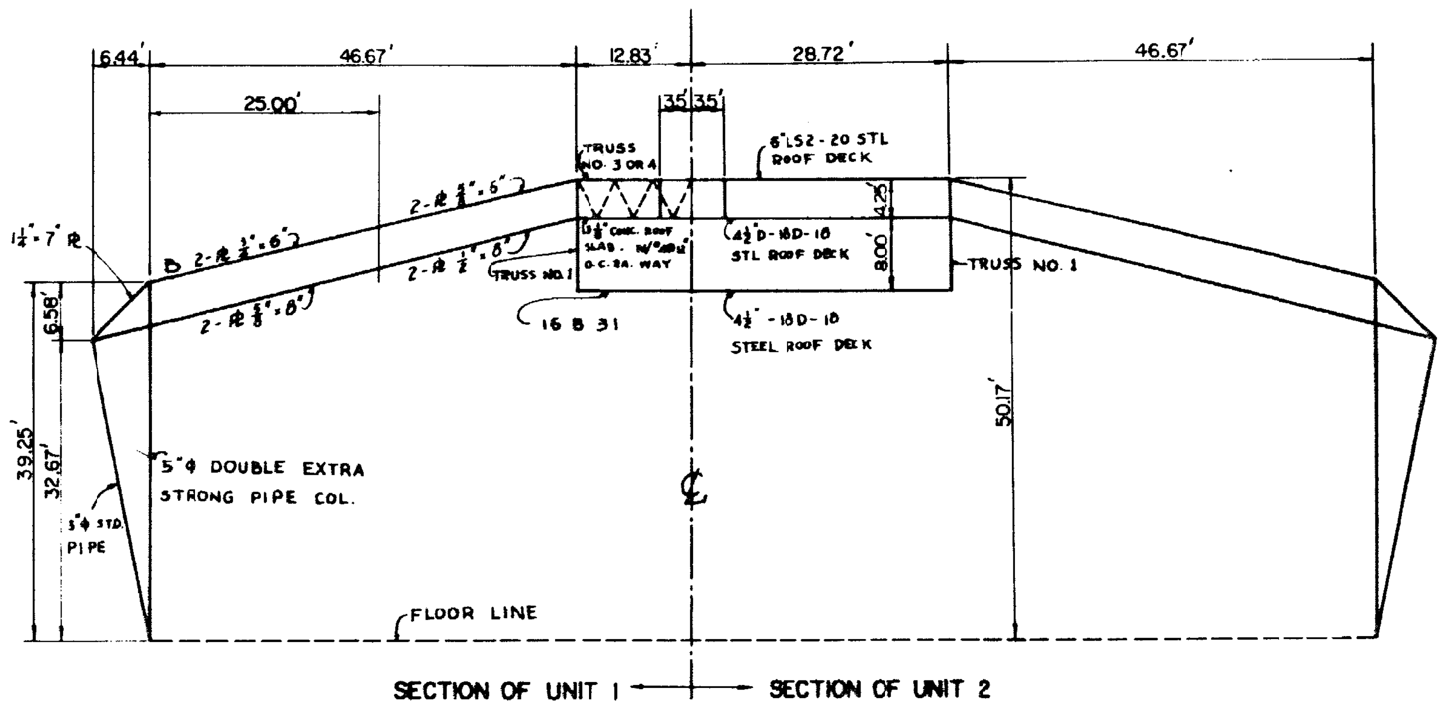



Fig. 2. Composite section of gymnasium.

Figure 3. Connection at equipment room.

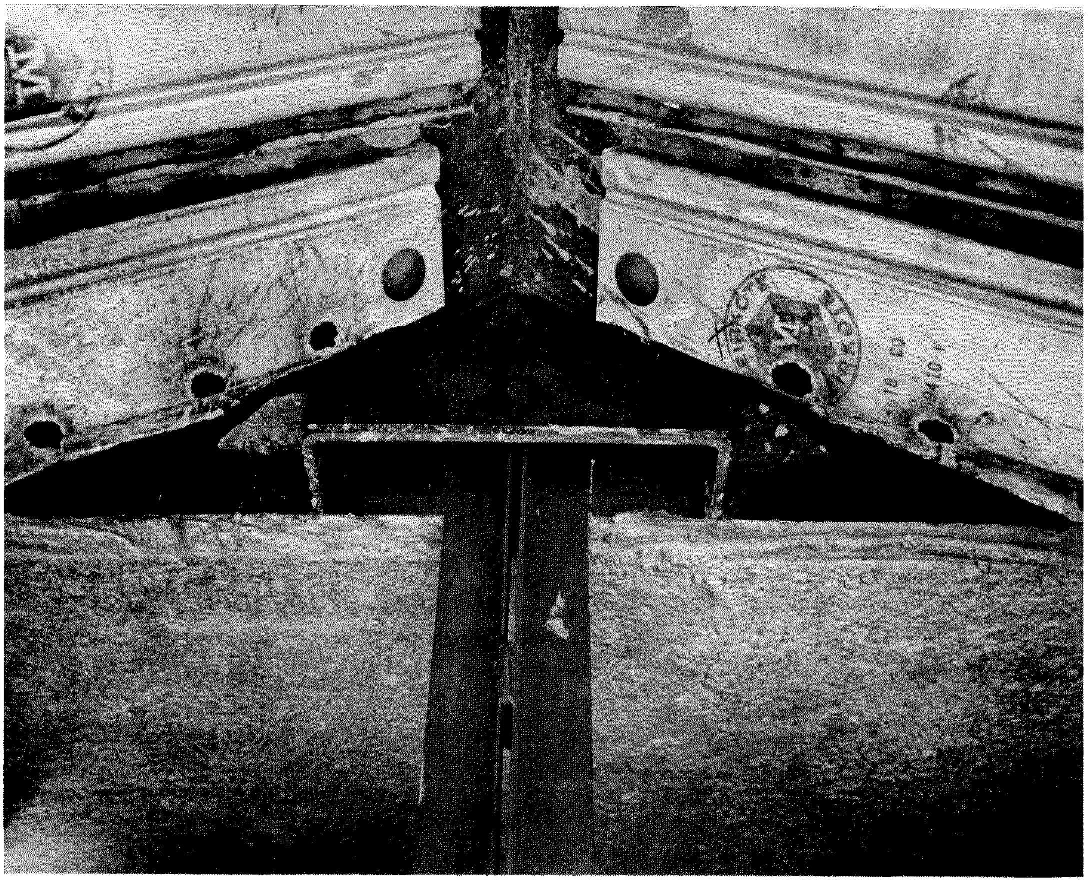


Figure 4. Roof valley member connection to equipment room.

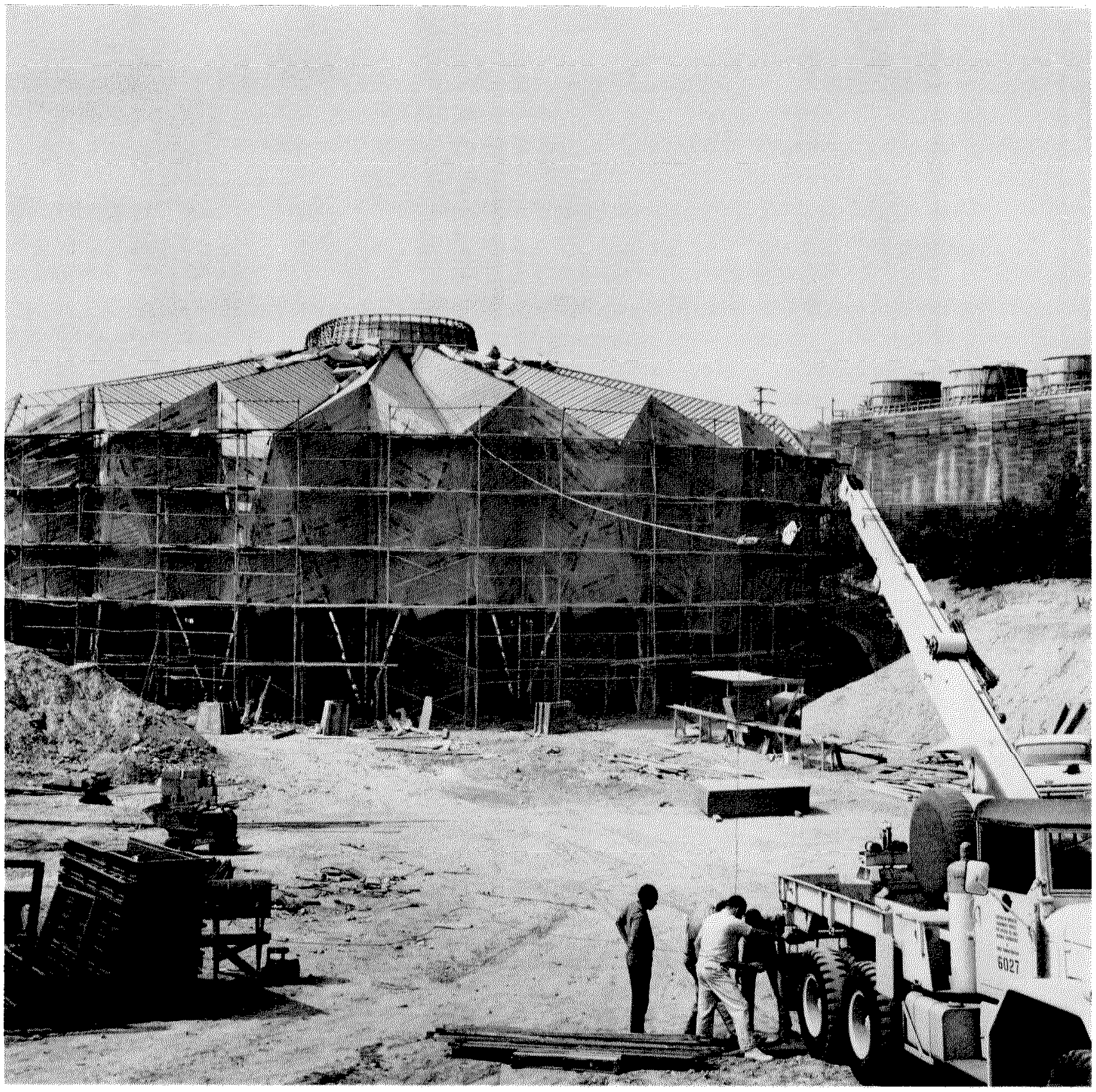


Figure 5. General view of gymnasium.

Figure 6. Roof structure.

At the completion of the roof structure all falsework were removed except those supporting the circumference of the equipment room. Figure 6 shows this stage of construction looking up at the equipment room from the concrete floor. The remaining sections of the concrete floor were placed to provide anchorage for the steel reinforcing bars used to resist horizontal motion of the column bases. A light-weight concrete slab was placed at the intermediate floor of the equipment room. During the last stages of the construction outlined above, strain gages were mounted by Caltech and JPL personnel so that when the contractor was ready to remove the roof support, the strain gages would be operational.

## STATIC INVESTIGATIONS

### A. Instrumentation

1. <u>JPL System.</u> Since the heart of this instrumentation system is the JPL developed automatic recorder whose output can be fed directly into a digital computer, this equipment will be briefly discussed in the present report. Full details are available in a JPL publication.

Each sensor (strain gage, transducer, or load cell), its cabling, and its balancing or bridge circuit comprise one channel. The total system consists of 4 banks of 50 channels each with two channels in each bank reserved for calibration data. Therefore, there are 48 data channels available in each bank. If all 4 banks are used (parallel operation), a maximum of 192 data channels would be available and could be connected to a single tape punch.

Each 50-channel bank contains balancing circuits, Speed-O-Max chart and voltmeter, and tape punch. During a scan of the channels, they are connected one by one to the voltmeter whose voltage is plotted by the Speed-O-Max and punched on paper tape. Since a maximum of two seconds is required to drive the voltmeter to a reading, a scan is made in 100 seconds. Six identification numbers are punched on the tape immediately preceding a data scan. This provides an identification of the data scan relative to date, time, scan code, and other necessary information.

Since only one bank was used for this investigation, the following discussion will be limited to one bank of 50 channels. Channels 1 and 2 were used to give the zero voltage and excitation voltage of the bank respectively. Thus, any drift of the system can be detected and later corrected digitally. In addition to the initial no-load gage reading scan and the actual data reading scans, two scans are needed to establish the necessary calibration and computation values for each channel. The former scan is made with a known resistance shunted across a known resistance leg of the balance bridge. The other scan is a manually punched scan which utilizes (for strain gages) the previous change in resistance calibration, and the gage factor of the active gage to convert the recorded output to convenient engineering units. The units used here are micro-inches per inch for the strain, pounds for the applied force, and degrees Fahrenheit for the temperature.

The single element strain gages installed by JPL were of the type FABW-25-12-S6 which were spot welded to the prepared metal surface of the structure. A slight difficulty in maintaining a resistance of 1000 Megohms or greater between the gage and ground was encountered with the weldable gages. It was suspected that the soldering flux residue left after installing the leads between the gage and the terminal strip was the culprit. Rosette gages of two types were placed on the sheet metal decking with an epoxy cement, EPY 150. The two types were FAR-50-12-45-S6 mounted by Caltech and C6-121-R3A mounted by JPL. One FABW-25-12-S6 and one FA-S0-12-S6 were attached by welding and EPY 150 respectively, to a laboratory beam to check the gage factors and operating characteristics of the two different gages. This beam was placed next to column 13 and was monitored throughout the entire test sequence.

It should be noted that these strain gages are self-temperature compensating to within a tolerance of ±1 micro-inch per inch per degree Fahrenheit when mounted on mild steel.

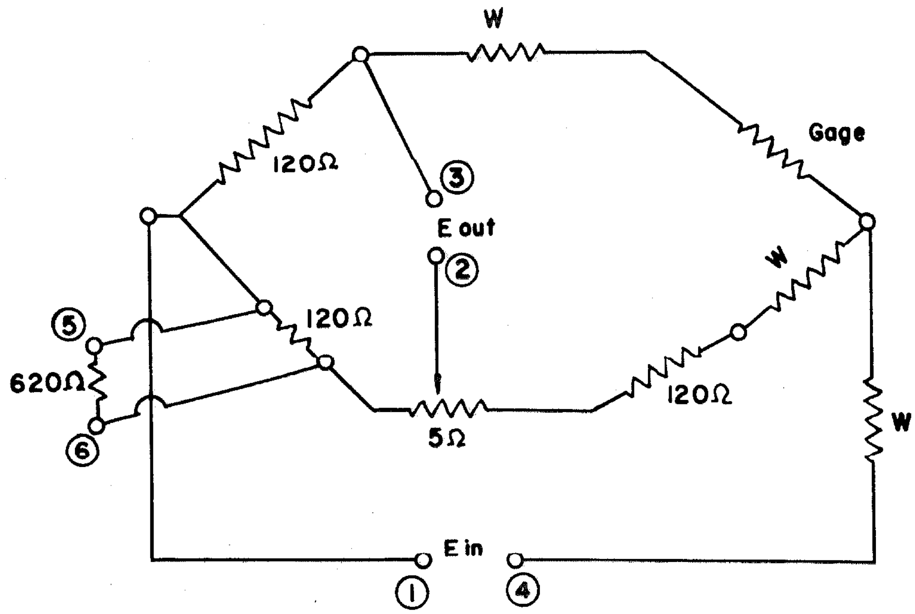
Each strain gage was connected with three lead wires (see Fig. 7) to minimize the lead wire effects. Approximately 100-foot lengths of six-conductor 26-gage copper wire were used between the strain gages and the completion boxes located in the instrument trailer. The loop resistance of the wire was about 8 ohms. The other three legs of the balance bridge were in the completion box with a variable resistor providing a course balance of the bridge.

Each completion box unit was connected to one channel of the automatic recording system with a six-conductor cable as indicated in Fig. 7. The fine balance of the bridge circuit was made with this unit. One D.C. amplifier was used to excite four bridges.

The thermocouple connections used for temperature measurements terminated in slightly different completion boxes before connecting into the automatic recording system.

In the case of the Alinco ±10, 000-pound capacity load cell used for the horizontal static load test, there was a direct connection between the load cell and the automatic recording system. Calibration of the load cell was identical to that of the strain gage bridge.

The paper tape with the six identification words per scan, the three preliminary calibration scans, and the data scans are transferred from




W = lead wire resistance

①··· = wires leading to the recording system

⑤⑥ = provide calibration shunt connection

Fig. 7. JPL completion box circuit.

paper tape to magnetic tape which is read into an IBM 7094 digital computer. The computer converts the raw data into engineering units data and can rework the data in any prescribed manner. The data presented here will be the raw data converted to engineering units.

2. Caltech System. The strain gages installed and monitored by Caltech were type FA-50-12-S6. The active gages and the corresponding dummy gages were mounted with either EPY 150 or Eastman 910 cement. The dummy gage was from the same lot as the corresponding active gage and it was mounted on a small piece of steel which was spot-cemented to the structure in the proximity of the active gage.

The active and dummy gages were connected on adjoining legs of a balanced bridge switch box with approximately ten feet of six-conductor 26-gage copper wire. The switch box had a capacity of 20 channels of which only 12 were used in this investigation. Figure 8 shows the circuit diagram of the switch box and the 1000 to 1 voltage reduction for the battery voltage read-out in millivolts. A polarity switch was also provided on this switching unit so that all voltages could be read as positive. The voltages were read and recorded manually from a 10mv full-scale Speed-O-Max voltmeter unit. The power supply was a nickel cadmium battery whose voltage was read at the beginning and end of each data scan.

Since the switch box did not contain a variable resistor, a completely balanced bridge circuit did not exist for the no-load condition of the strain gage. Therefore, the initial readings of voltage output divided by voltage supplied had to be subtracted from the test readings to give effective strains.

Two gages were laboratory mounted to opposite sides of a cantilever beam with one gage mounted with EPY 150 and the other gage with

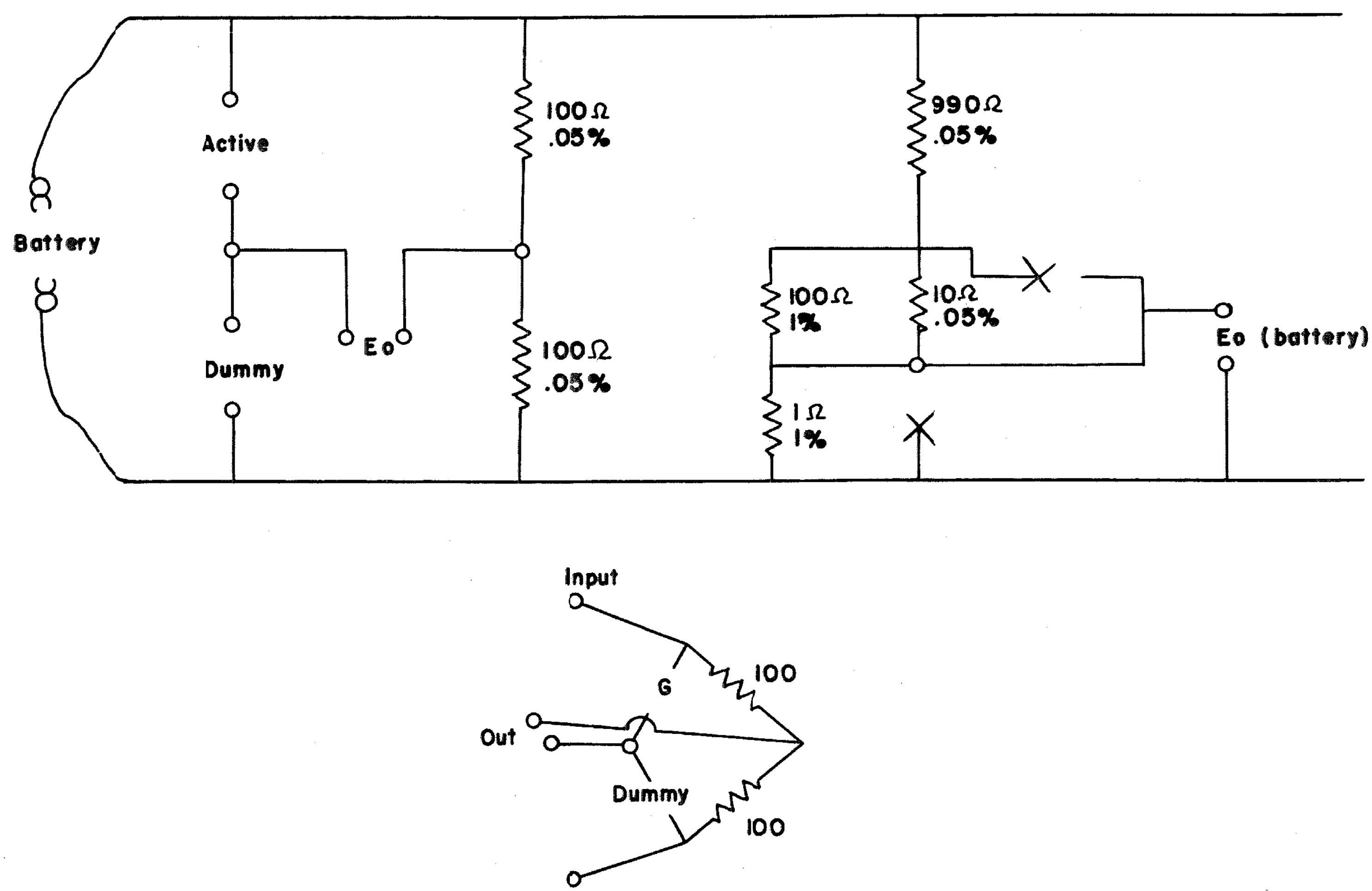



Fig. 8. Caltech switch box circuit.

Eastman 910 cement. These gages were applied under the same conditions and by the same techniques as the field gages. The purposes of the laboratory tests of this beam were to check the reliability of the instrumentation, gages, and cement and to determine the installation's effect on the gage factor given by the manufacturer. The results of the laboratory tests of one gage mounted with each type of cement follow:

For the gage mounted with Eastman 910 cement, the strain measured under a given loading condition was 347 micro-inches per inch in compression and 337 micro-inches per inch in tension. For the gage mounted with EPY 150 the measured tension strain for the same loading condition was 370 micro-inches per inch. The maximum range of the strain readings was ±5 micro-inches per inch which corresponds to the expected reading error associated with the equipment. The theoretical strain in the cantilever beam for an assumed modulus of elasticity of $29 \times 10^6$ psi is 354 micro-inches per inch. These laboratory tests indicate that the measured strain should be accurate within ±5%.

The tabulated output data will be given in this report in terms of micro-inches per inch. The equation used for this data reduction is

$$\epsilon = \frac{4000}{\text{g.f.}}\left[\left(\frac{E_o}{V}\right)_{\text{data}} - \left(\frac{E_o}{V}\right)_{\text{initial}}\right]$$

where $\epsilon$ is the strain in micro-inches per inch, $\frac{E_o}{V}$ is the ratio of the output voltage to the excitation voltage times 1000, and "g.f." is the gage factor of the active and dummy gages. The change in strain for any change in loading condition can be determined by subtracting the strains at the two conditions.

3. <u>Gage Location and Identification</u>. All of the gages were mounted on the major structural members near the column to roof-member connections. The only exceptions to this were the rosette gages which were placed on the stress-carrying metal of the roof deck. Holes four inches in diameter were cut through the hat section of the metal deck to permit access to the top surface of the stress-carrying deck for rosette installation. These gages are located on the structure as indicated in Fig. 1, and the orientation and numbering details are given in Figs. 9 and 10. Figure 11 shows gages 40, 41 and 42 with the lead wires soldered to the terminal strips. A piece of tape was used to cover the hole in the hat section keeping direct sunlight from the gage installation.

The location of the single element gages are given in Figs. 9, 10 and 12 where the dashed lines are used to indicate gages placed on the "interior" side of the member. The column position numbers are related to Fig. 1. Typical gage installations are shown in Figs. 13 and 14. Note that the gage numbers in the photographs are not the same as the tabulated data.

Gages 3 through 35 inclusive were welded and gages 4T, 5T, 6T and 7T and one-half of laboratory beam were mounted with Eastman 910 cement. The remainder of the gages were mounted with EPY 150.

B. <u>Roof Support Removal</u>.

The roof fold members were supported along their length prior to and while the sheet metal decking was welded in place. After the decking was completely welded and the welds inspected, all the fold member supports were removed so that the concrete floor could be placed. It was important to have the concrete floor in place and partially cured before letting the structure carry its own weight because the bottom of

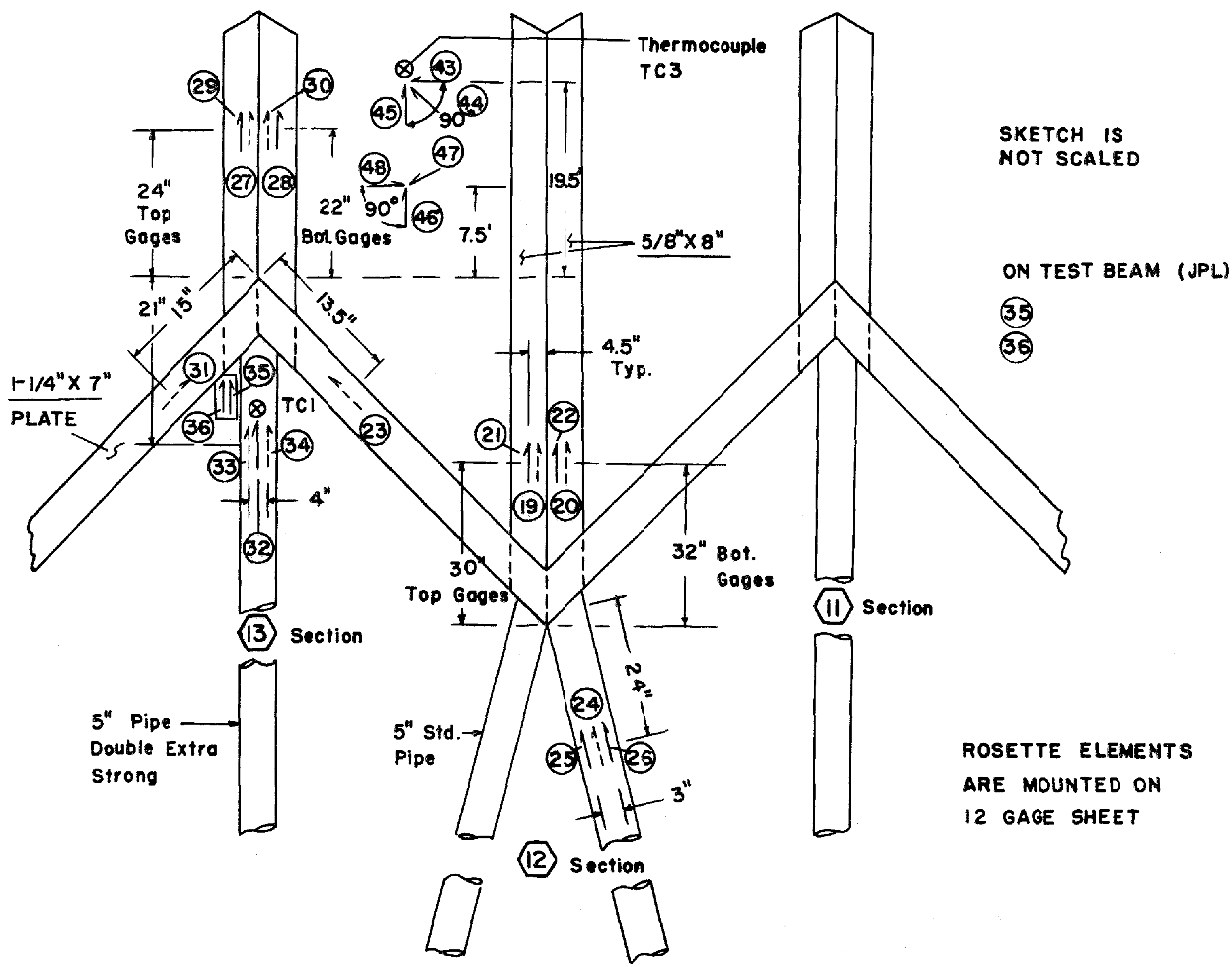
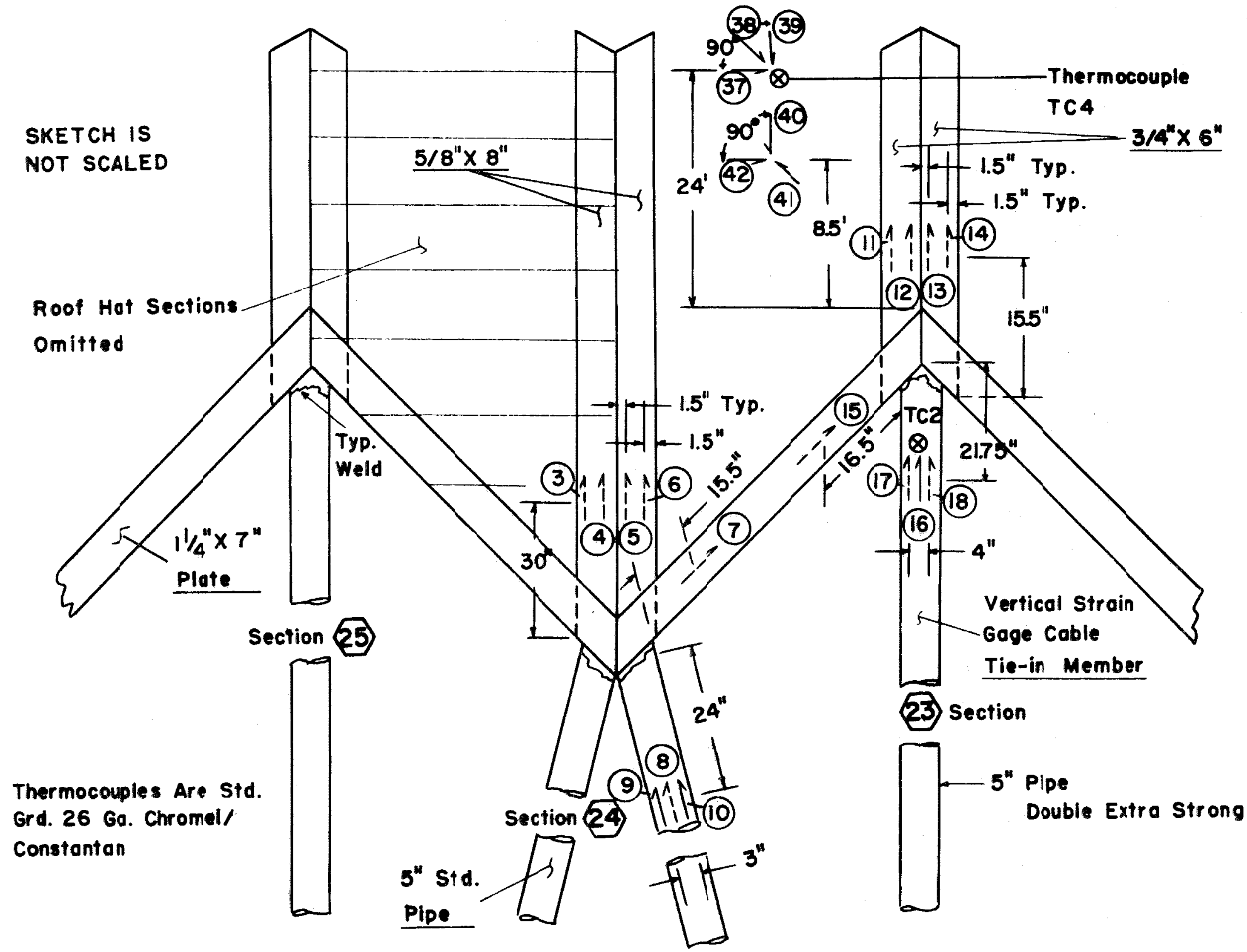



Fig. 9. Location of gages.




FRONT VIEW. MINOR AXIS STRAIN GAGE POSITIONS

Fig. 10. Location of gages.

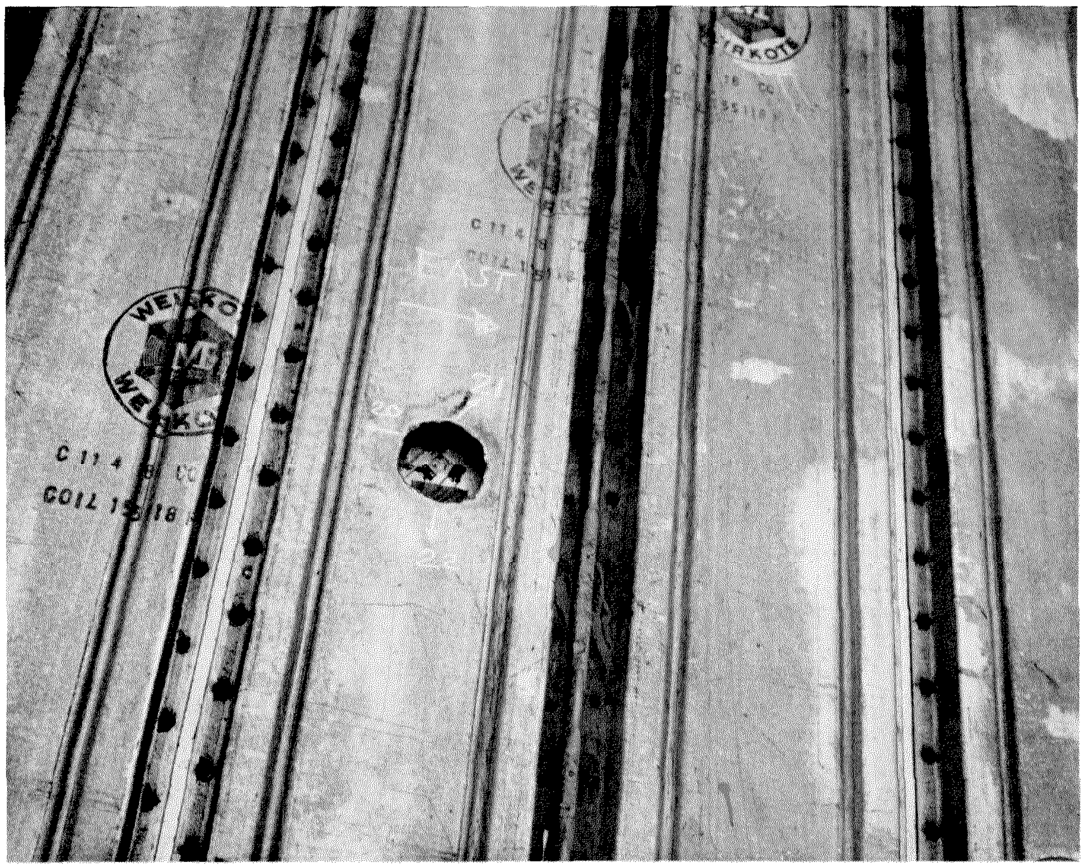
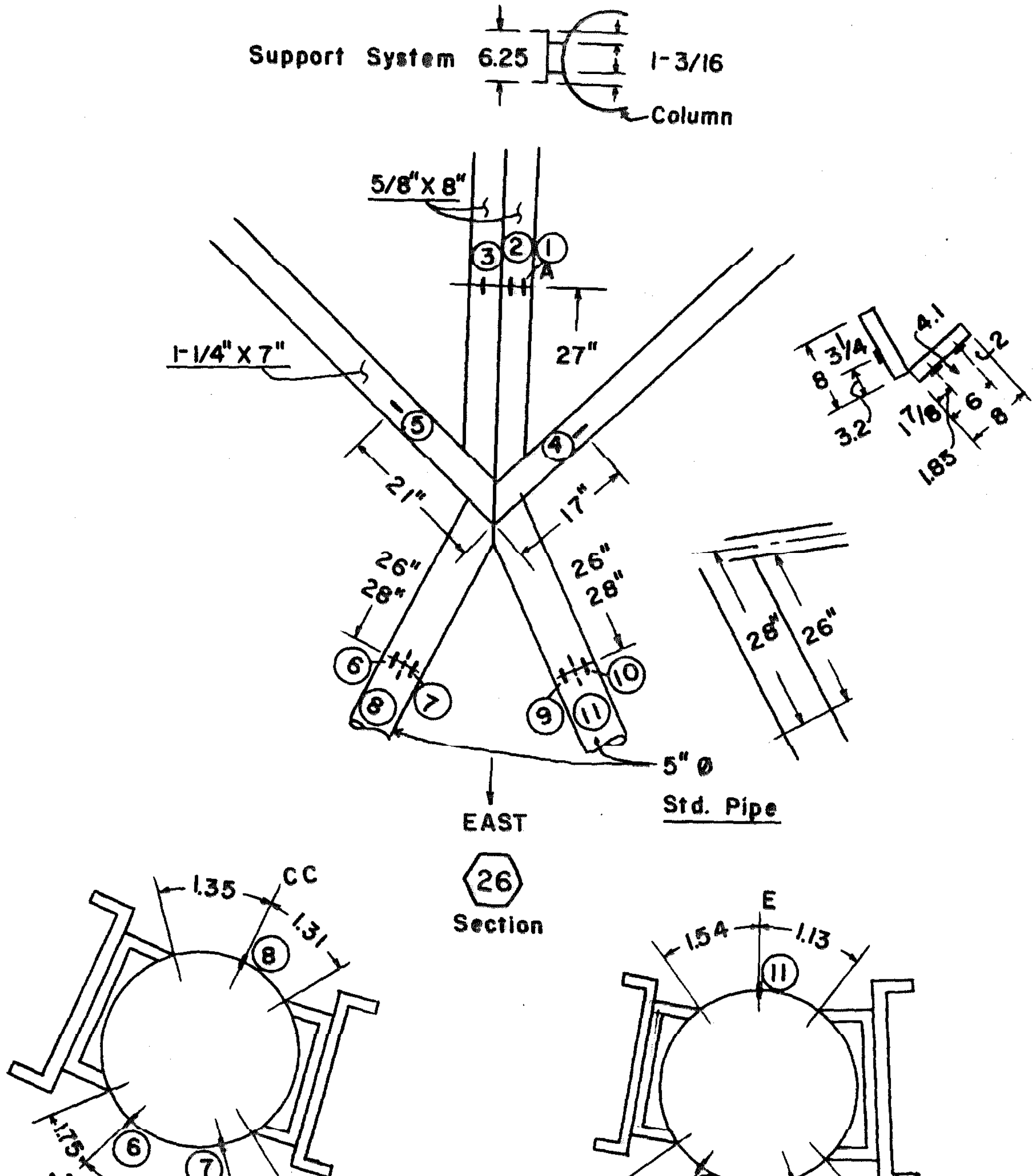



Figure 11. Typical gage locations.




Section Monitored by Caltech
Location: first valley south of east minor axis valley
All gage numbers should be followed by a 'T'

Fig. 12. Location of gages.

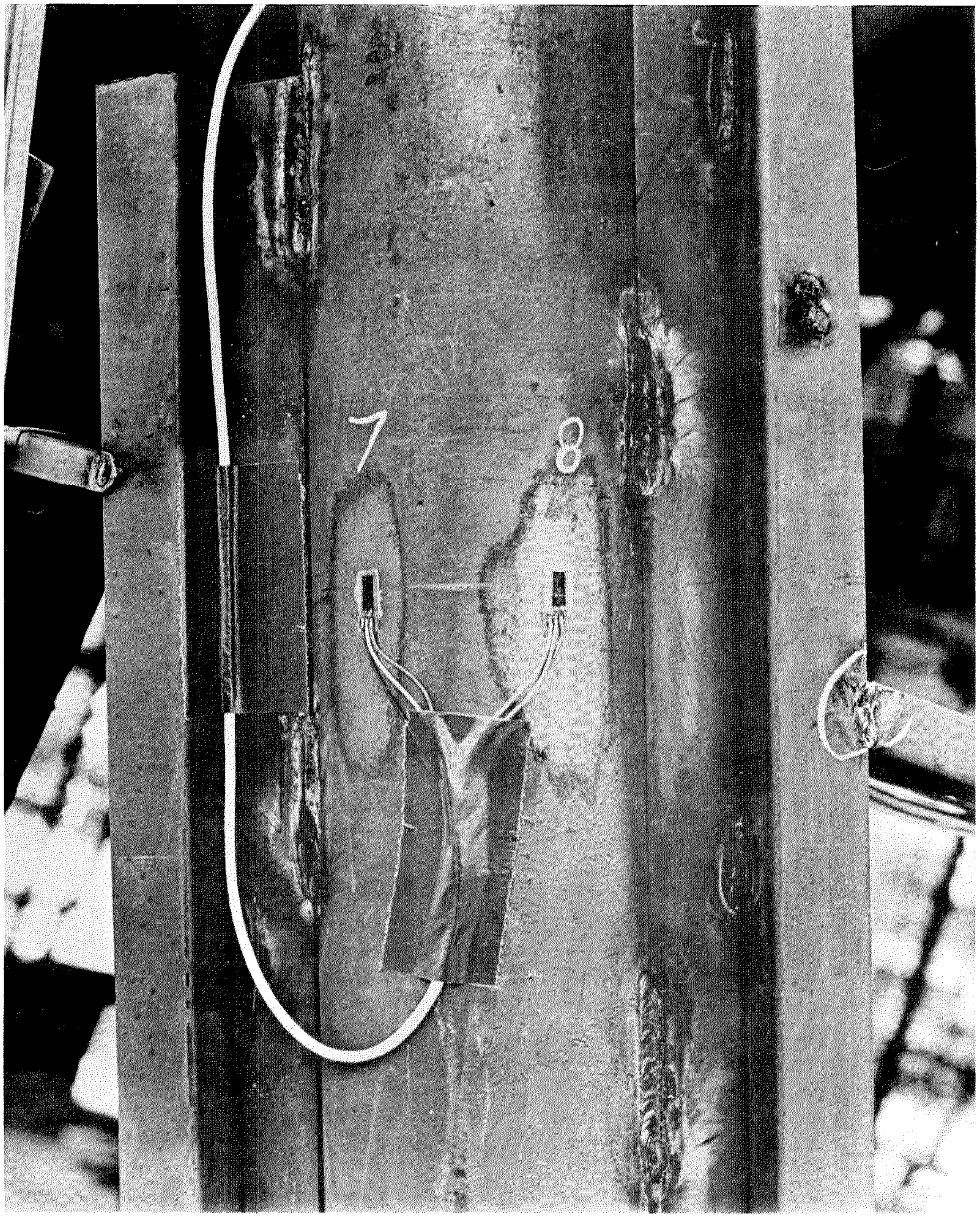



Figure 13. Typical gage installation.

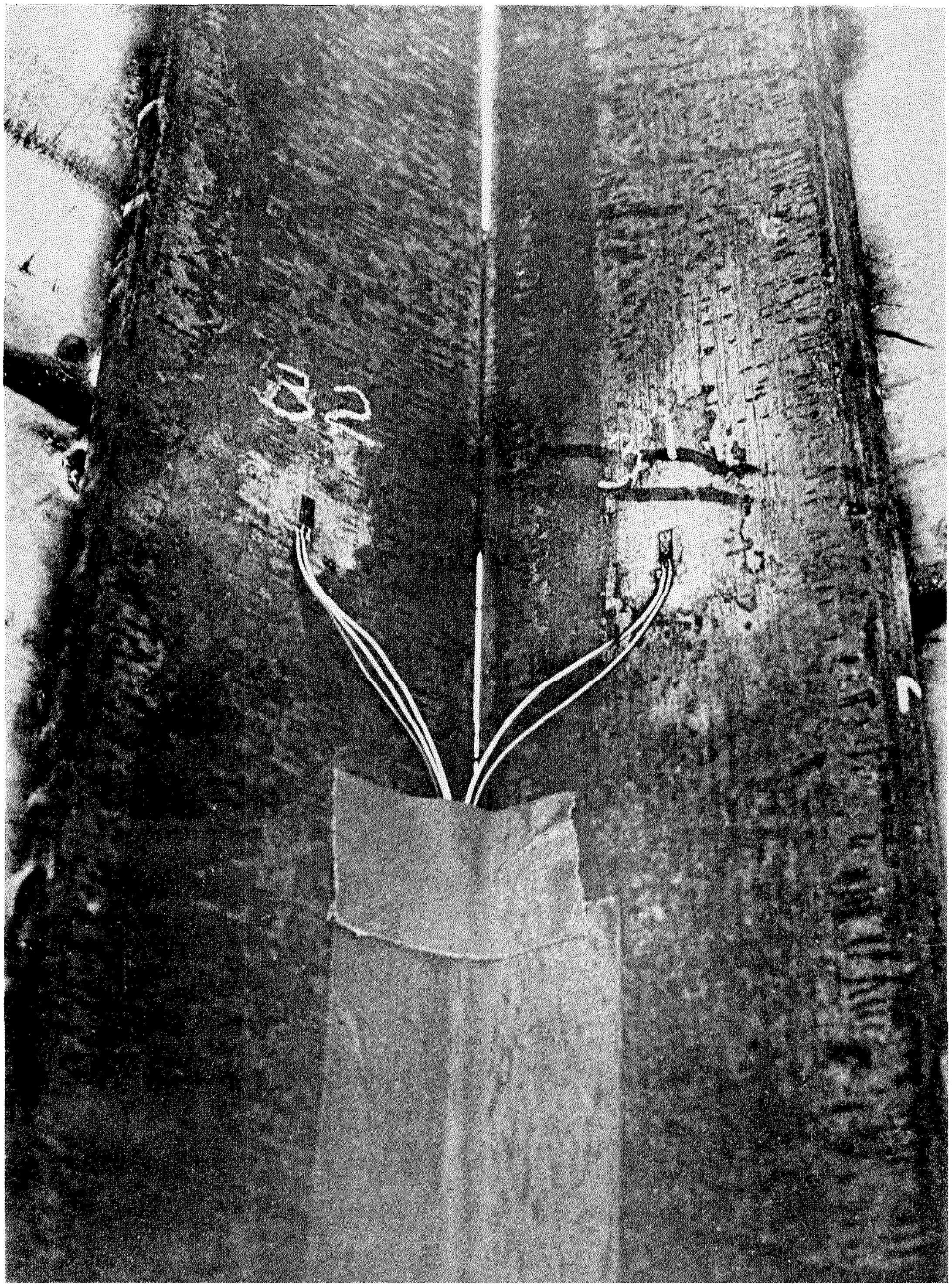



Figure 14. Typical gage installation.

the columns were tied into the concrete floor with 7/8-inch diameter reinforcing bars to resist all lateral forces at the base.

The lightweight concrete floor at the center level of the equipment room was in place and cured before the test. The ridge fold members were supported vertically on level steel ears but were free to move horizontally (Fig. 3). The valley members framing into the center level of the equipment room were bolted into their final position (Fig. 4). At the time of the roof support removal the roof was entirely self-supporting except for the original falsework supporting the roof around the outside ring at the bottom of the equipment room. Thus, the test could be thought of as applying a vertical line load to the structure at the outside ring of the equipment room.

The roof supports were removed during the morning of 14 June 1965. About 8 a.m. the contractor began loosening some of the intermediate roof supports at the top of the support. One steel tape suspended from each end of the principal axes of the equipment room was used by the contractor to make sure that the structure deflected uniformly. The contractor also had instructions to halt the support removal when the deflection reached three inches. In addition, a level rod was fixed at the top level of the equipment room near the centerline of the structure. This level rod was read by a fixed transit placed about 200 feet away.

The roof support system had threaded end pieces at both the top and bottom ends. The unloading procedure began by loosening all the bottom end pieces one turn in a random sequence. This procedure continued until each piece was rotated until it turned easily. This procedure was continued until the structure was free-standing with about 1/8-inch clearance between the structure and its former supports.

The deflection of the structure under its own weight was 1-1/4 inches measured both by the transit and as an average of the tape readings. The range of the four tape readings was 1-1/8 inch to 1-1/2 inch. During the morning the sky was moderately overcast with the sun breaking through infrequently for short intervals of time. It was observed that the effect of the sun shining on the structure for a short time caused the roof center to rise at least 1/4 inch. Also, about a 1/4-inch deflection decrease was observed when eight spectators left the roof after the unloading had been completed.

The results presented here are separated into two groups: those taken with the JPL instrumentation and those observed with the Caltech instrumentation. These two groups of results can be compared only at data-taking points near the same times. It should be mentioned here that three minutes were required to take a complete set of data with the Caltech equipment (12 channels) and two minutes with the JPL equipment (50 channels).

Table I presents the reduced data taken with the Caltech instrumentation. The identification of the data channels to specific strain gage locations can be made with Fig. 12. All data is presented in micro-inches per inch. Table II presents the data taken by JPL and the units are micro-inches per inch for the strain and degrees Fahrenheit for the temperatures. These gages may be located with Figs. 8 and 9.

## C. Temperature-Stress Investigation.

It was decided that a twenty-four hour check of the temperature stress variation of the structure would be of value. The automatic recording system is ideal for this type of test because only periodic checks

TABLE I

CALTECH DATA - SUPPORT REMOVAL

| Time | June 8 | June 14 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Afternoon | Morning before 8:45 | | | 8:45 | 8:50 | 8:55 | 9:00 | 9:05 | 9:10 | 9:15 | 9:20 | 9:25 |
| 1T | - 84 | - 2 | 6 | 2 | - 26 | - 28 | - 30 | - 38 | - 39 | - 51 | - 53 | - 64 | - 73 |
| 2T | - 56 | 2 | 6 | 4 | - 36 | - 45 | - 56 | - 62 | - 68 | - 84 | - 92 | -107 | -113 |
| 3T | -161 | 5 | 10 | -111 | -171 | -182 | -185 | -199 | -204 | -220 | -227 | -240 | -248 |
| 4T | -668 | -10 | - 25 | - 27 | - 14 | - 42 | - 44 | - 52 | - 58 | - 68 | - 69 | - 77 | - 81 |
| 5T | 973 | 120 | 97 | 100 | 100 | 147 | 143 | 153 | 150 | 154 | 160 | 172 | 178 |
| 6T | -147 | 14 | 37 | 33 | 41 | 42 | 35 | 46 | 44 | 48 | 48 | 46 | 46 |
| 7T | -107 | 6 | 11 | 9 | 8 | 15 | 8 | 9 | 9 | 15 | 10 | 8 | 8 |
| 8T | 368 | 13 | 21 | 25 | 50 | 64 | 62 | 75 | 75 | 93 | 93 | 104 | 108 |
| 9T | -148 | -15 | -210 | -210 | -193 | -188 | -184 | -184 | -176 | -180 | -172 | -176 | -165 |
| 10T | 13 | 4 | 8 | 8 | 9 | 17 | 19 | 19 | 23 | 21 | 24 | 30 | 34 |
| 11T | - 4 | - 9 | - 17 | - 17 | 11 | 17 | 28 | 34 | 41 | 51 | 62 | 71 | 81 |
| 12T | | - 7 | - 19 | - 21 | - 17 | - 11 | - 11 | - 13 | - 13 | - 15 | - 11 | - 13 | - 13 |

TABLE I (Continued)

CALTECH DATA - SUPPORT REMOVAL

| Time | June 14 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 9:30 | 9:35 | 9:40 | 9:45 | 9:50 | 9:55 | 10:00 | 10:06 | 10:10 | 10:15 | 10:25 | 10:37 | 10:56 | 11:02 |
| 1T | - 81 | - 86 | - 98 | -101 | - 98 | -109 | -111 | -109 | -111 | -103 | -103 | -129 | -111 | -103 |
| 2T | -127 | -142 | -159 | -170 | -169 | -182 | -178 | -180 | -178 | -182 | -184 | -188 | -180 | -182 |
| 3T | -259 | -272 | -294 | -304 | -300 | -315 | -315 | -303 | -303 | -303 | -315 | -303 | -311 | -311 |
| 4T | - 91 | -100 | -108 | -116 | -128 | -124 | -124 | -125 | -125 | -124 | -118 | - 97 | -118 | -120 |
| 5T | 189 | 193 | 206 | 216 | 212 | 212 | 212 | 222 | 216 | 212 | 212 | 239 | 212 | 212 |
| 6T | 48 | 54 | 58 | 62 | 68 | 66 | 62 | 64 | 58 | 62 | 62 | 33 | 62 | 62 |
| 7T | 9 | 17 | 17 | 21 | 24 | 21 | 21 | 8 | 11 | 10 | 10 | 2 | 10 | 30 |
| 8T | 120 | 133 | 147 | 156 | 162 | 160 | 154 | 158 | 158 | 156 | 160 | 152 | 174 | 174 |
| 9T | -161 | -161 | -158 | -154 | -152 | -154 | -154 | -150 | -143 | -144 | -150 | -129 | -148 | -142 |
| 10T | 38 | 41 | 41 | 45 | 51 | 49 | 49 | 49 | 49 | 51 | 51 | 49 | 52 | 49 |
| 11T | 92 | 99 | 104 | 129 | 128 | 131 | 133 | 131 | 137 | 135 | 135 | 154 | 140 | 139 |
| 12T | - 15 | - 17 | - 11 | - 13 | - 17 | - 13 | - 15 | - 17 | - 15 | - 15 | - 13 | - 6 | - 9 | - 15 |

TABLE II

JPL DATA — SUPPORT REMOVAL

| Time | 7:52 | 7:55 | 8:00 | 8:15 | 8:30 | 8:35 | 8:40 | 8:45 | 8:50 | 8:55 | 9:00 | 9:05 | 9:10 | 9:15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gage No. | | | | | | | | | | | | | | |
| 3 | -7 | -7 | -12 | 0 | -7 | -2 | -9 | -16 | -30 | -32 | -44 | -44 | -51 | -58 |
| 4 | 7 | 7 | 7 | 9 | 12 | -12 | -12 | -25 | -39 | -44 | -55 | -62 | -77 | -88 |
| 5 | 2 | 0 | 0 | 0 | -5 | -25 | -30 | -46 | -60 | -62 | -76 | -86 | -104 | -116 |
| 6 | -16 | -19 | -23 | -23 | -40 | -26 | -40 | -51 | -60 | -67 | -79 | -81 | -91 | -100 |
| 7 | -7 | -7 | -12 | 0 | -5 | 25 | -23 | 37 | 46 | 51 | 58 | 62 | 79 | 81 |
| 8 | -5 | -5 | -5 | -5 | 2 | 9 | 18 | 30 | 35 | 44 | 51 | 58 | 69 | 76 |
| 9 | -7 | -9 | -19 | -12 | -16 | 0 | 0 | 5 | 5 | 7 | 5 | 5 | 9 | 9 |
| 10 | 5 | 5 | 7 | 9 | 12 | 9 | 14 | 21 | 25 | 30 | 32 | 32 | 37 | 39 |
| 11 | -7 | -7 | -14 | -11 | -7 | 23 | 18 | 30 | 39 | 44 | 53 | 60 | 76 | 83 |
| 12 | 2 | 2 | 0 | -5 | 2 | 5 | 16 | 23 | 37 | 41 | 52 | 55 | 66 | 73 |
| 13 | 0 | 2 | 0 | -2 | 9 | 5 | 16 | 30 | 37 | 41 | 55 | 60 | 69 | 78 |
| 14 | -7 | -9 | -12 | -7 | -7 | 23 | 18 | 25 | 39 | 41 | 48 | 53 | 72 | 74 |
| 15 | -14 | -14 | -18 | -11 | -7 | 30 | 25 | 37 | 44 | 50 | 60 | 64 | 83 | 90 |
| 16 | 2 | 5 | 2 | 7 | 12 | -11 | 2 | 0 | -5 | -5 | -9 | -14 | -16 | -18 |
| 17 | -14 | -16 | -21 | -16 | -25 | -2 | -16 | -25 | -32 | -37 | -48 | -51 | -53 | -58 |
| 18 | -0 | 0 | 2 | 5 | 9 | -7 | -5 | -9 | -21 | -21 | -28 | -30 | -39 | -44 |
| 19 | 0 | 0 | -2 | 0 | -5 | -11 | -23 | -43 | -46 | -59 | -71 | -85 | -96 | -101 |
| 20 | -5 | -5 | -9 | -12 | -21 | -28 | -39 | -58 | -67 | -78 | -92 | -106 | -120 | -125 |
| 21 | -7 | -7 | -14 | -9 | -16 | -5 | -18 | -39 | -41 | -53 | -67 | -76 | -83 | -90 |
| 22 | 2 | 2 | 7 | 7 | 7 | -11 | -16 | -28 | -30 | -39 | -48 | -55 | -69 | -69 |
| 23 | -5 | -5 | -9 | -5 | 0 | 14 | 18 | 30 | 37 | 46 | 57 | 62 | 76 | 78 |
| 24 | -2 | -2 | -2 | 0 | 5 | 21 | 25 | 37 | 41 | 55 | 67 | 74 | 88 | 90 |
| 25 | -12 | -12 | -19 | -16 | -19 | 2 | -2 | -2 | 2 | 0 | -2 | 0 | 7 | 5 |
| 26 | 2 | 2 | 2 | 5 | 9 | 7 | 9 | 14 | 16 | 16 | 18 | 16 | 21 | 23 |
| 27 | 2 | 0 | 2 | 7 | 25 | 5 | 30 | 41 | 50 | 59 | 71 | 73 | 87 | 92 |
| 28 | 2 | 5 | 5 | 16 | 28 | 41 | 46 | 57 | 64 | 71 | 80 | 85 | 96 | 101 |
| 29 | -7 | -7 | -16 | -7 | -7 | 19 | 16 | 19 | 25 | 28 | 35 | 39 | 53 | 56 |
| 30 | 2 | 0 | 2 | 5 | 16 | 18 | 27 | 37 | 44 | 50 | 59 | 62 | 73 | 78 |
| 31 | -2 | -2 | -5 | -5 | -2 | 9 | 14 | 28 | 34 | 39 | 50 | 53 | 64 | 69 |
| 32 | -2 | -2 | -7 | -5 | -5 | -28 | -14 | -18 | -21 | -23 | -28 | -32 | -35 | -37 |
| 33 | -14 | -14 | -19 | -16 | -21 | -14 | -19 | -37 | -42 | -51 | -62 | -65 | -70 | -70 |
| 34 | 0 | 0 | 0 | 0 | 0 | -14 | -12 | -16 | -23 | -25 | -32 | -37 | -44 | -44 |
| 35 | -7 | -7 | -14 | -5 | -5 | 7 | 7 | 0 | 5 | 5 | 0 | 0 | 5 | 5 |
| 36 | 4 | 6 | 8 | 15 | 23 | 19 | 25 | 30 | 30 | 32 | 34 | 36 | 38 | 40 |
| 37 | -13 | -13 | -16 | 13 | 22 | 67 | 65 | 54 | 56 | 58 | 61 | 74 | 85 | 85 |
| 38 | 9 | 11 | 13 | 18 | 29 | 13 | 27 | 35 | 38 | 44 | 53 | 49 | 53 | 58 |
| 39 | 11 | 16 | 18 | 22 | 36 | 29 | 34 | 43 | 47 | 51 | 56 | 54 | 61 | 63 |
| 40 | -2 | 0 | -2 | 11 | 21 | 36 | 38 | 38 | 46 | 46 | 46 | 49 | 57 | 61 |
| 41 | 4 | 6 | 6 | 17 | 25 | 30 | 32 | 40 | 42 | 44 | 48 | 49 | 55 | 55 |
| 42 | -6 | -6 | -8 | 13 | 21 | 53 | 57 | 49 | 49 | 51 | 51 | 57 | 68 | 68 |
| 43 | -2 | 0 | 0 | 20 | 31 | 51 | 60 | 56 | 60 | 56 | 63 | 72 | 81 | 85 |
| 44 | 2 | 2 | 4 | 13 | 18 | 18 | 18 | 20 | 20 | 22 | 26 | 27 | 24 | 27 |
| 45 | 2 | 2 | 7 | 13 | 18 | 16 | 18 | 20 | 20 | 22 | 29 | 27 | 27 | 31 |
| 46 | -2 | 0 | -4 | 6 | 15 | 17 | 29 | 23 | 32 | 29 | 29 | 34 | 38 | 40 |
| 47 | 8 | 10 | 15 | 52 | 67 | 69 | 73 | 88 | 89 | 90 | 94 | 94 | 99 | 99 |
| 48 | -4 | -4 | -8 | 4 | 15 | 29 | 36 | 32 | 36 | 34 | 34 | 44 | 51 | 57 |
| TC1 | 58 | | | 58 | | 59 | | | 59 | | 60 | | 60 | |
| TC2 | 60 | | | 60 | | 61 | | | 63 | | 63 | | 63 | |
| TC3 | | 65 | 64 | | 66 | | 66 | 68 | | 68 | | 68 | | 70 |
| TC4 | | 66 | 65 | | 66 | | 71 | 71 | | 72 | | 72 | | 73 |

TABLE II (Continued)

JPL DATA — SUPPORT REMOVAL

| Time / Gage No. | 9:20 | 9:25 | 9:30 | 9:35 | 9:40 | 9:45 | 9:50 | 9:55 | 10:00 | 10:05 | 10:10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | -58 | -60 | -69 | -83 | -102 | -102 | -100 | -108 | -93 | -93 | -86 |
| 4 | -99 | -111 | -124 | -136 | -159 | -173 | -178 | -173 | -178 | -173 | -178 |
| 5 | -125 | -139 | -152 | -166 | -190 | -206 | -211 | -208 | -213 | -211 | -218 |
| 6 | -100 | -104 | -116 | -132 | -154 | -151 | -151 | -163 | -147 | -149 | -145 |
| 7 | 97 | 106 | 118 | 118 | 127 | 145 | 152 | 148 | 164 | 162 | 169 |
| 8 | 83 | 97 | 111 | 118 | 129 | 141 | 141 | 148 | 145 | 150 | 146 |
| 9 | 23 | 30 | 30 | 28 | 23 | 35 | 39 | 28 | 44 | 44 | 51 |
| 10 | 41 | 46 | 48 | 55 | 57 | 60 | 57 | 64 | 60 | 60 | 58 |
| 11 | 99 | 108 | 117 | 126 | 138 | 154 | 156 | 154 | 165 | 165 | 168 |
| 12 | 80 | 87 | 98 | 114 | 123 | 132 | 133 | 135 | 128 | 135 | 130 |
| 13 | 83 | 90 | 103 | 115 | 129 | 136 | 134 | 140 | 134 | 138 | 134 |
| 14 | 92 | 99 | 115 | 115 | 125 | 141 | 143 | 141 | 152 | 150 | 155 |
| 15 | 108 | 117 | 135 | 133 | 142 | 167 | 168 | 163 | 186 | 179 | 186 |
| 16 | -21 | -28 | -30 | -30 | -39 | -39 | -41 | -37 | -41 | -37 | -44 |
| 17 | -55 | -57 | -60 | -78 | -94 | -90 | -92 | -97 | -81 | -83 | -76 |
| 18 | -55 | -55 | -60 | -65 | -81 | -88 | -90 | -85 | -88 | -85 | -88 |
| 19 | -119 | -132 | -146 | -157 | -178 | -180 | -190 | -185 | -185 | -183 | -188 |
| 20 | -140 | -154 | -170 | -184 | -205 | -211 | -214 | -216 | -214 | -214 | -217 |
| 21 | -92 | -103 | -110 | -131 | -150 | -149 | -150 | -152 | -145 | -145 | -143 |
| 22 | -82 | -96 | -110 | -112 | -128 | -135 | -135 | -135 | -140 | -137 | -145 |
| 23 | 94 | 106 | 119 | 126 | 134 | 149 | 147 | 147 | 150 | 152 | 152 |
| 24 | 106 | 115 | 129 | 137 | 150 | 159 | 157 | 157 | 164 | 166 | 166 |
| 25 | 19 | 21 | 25 | 14 | 12 | 23 | 21 | 21 | 28 | 28 | 37 |
| 26 | 23 | 27 | 27 | 32 | 32 | 34 | 32 | 34 | 30 | 34 | 30 |
| 27 | 105 | 114 | 123 | 135 | 149 | 155 | 155 | 158 | 158 | 162 | 163 |
| 28 | 115 | 123 | 133 | 139 | 149 | 158 | 160 | 160 | 163 | 165 | 168 |
| 29 | 72 | 81 | 95 | 85 | 93 | 109 | 106 | 109 | 116 | 113 | 123 |
| 30 | 85 | 94 | 101 | 114 | 124 | 128 | 128 | 128 | 128 | 128 | 126 |
| 31 | 83 | 92 | 99 | 112 | 122 | 131 | 129 | 131 | 129 | 133 | 136 |
| 32 | -37 | -46 | -46 | -51 | -58 | -55 | -58 | -55 | -55 | -53 | -53 |
| 33 | -74 | -79 | -79 | -99 | -111 | -106 | -109 | -109 | -102 | -102 | -97 |
| 34 | -53 | -57 | -67 | -67 | -78 | -80 | -83 | -83 | -83 | -78 | -85 |
| 35 | 12 | 14 | 18 | 7 | 5 | 14 | 9 | 14 | 16 | 16 | 23 |
| 36 | 40 | 44 | 44 | 50 | 51 | 53 | 55 | 57 | 57 | 59 | 57 |
| 37 | 99 | 112 | 132 | 96 | 94 | 123 | 132 | 130 | 164 | 153 | 171 |
| 38 | 60 | 62 | 64 | 75 | 82 | 82 | 82 | 84 | 80 | 82 | 80 |
| 39 | 63 | 65 | 63 | 78 | 83 | 80 | 78 | 85 | 78 | 85 | 81 |
| 40 | 67 | 74 | 78 | 74 | 72 | 80 | 82 | 84 | 93 | 97 | 108 |
| 41 | 61 | 65 | 72 | 69 | 70 | 76 | 80 | 82 | 86 | 86 | 91 |
| 42 | 78 | 91 | 105 | 80 | 72 | 95 | 103 | 101 | 129 | 122 | 135 |
| 43 | 94 | 107 | 110 | 98 | 101 | 118 | 128 | 123 | 143 | 139 | 153 |
| 44 | 24 | 26 | 27 | 33 | 33 | 33 | 33 | 35 | 35 | 38 | 35 |
| 45 | 31 | 31 | 33 | 38 | 38 | 40 | 38 | 42 | 42 | 47 | 40 |
| 46 | 46 | 52 | 57 | 46 | 44 | 57 | 59 | 59 | 67 | 67 | 80 |
| 47 | 88 | 100 | 102 | 109 | 107 | 109 | 107 | 108 | 109 | 113 | 107 |
| 48 | 61 | 71 | 76 | 63 | 61 | 78 | 84 | 80 | 95 | 93 | 105 |
| TC1 | 61 | | 62 | | 62 | | 62 | | 63 | | 64 |
| TC2 | 64 | | 64 | | 64 | | 65 | | 66 | | 66 |
| TC3 | | 71 | | 73 | | 73 | | 73 | | 75 | |
| TC4 | | 75 | | 76 | | 74 | | 76 | | 80 | |

TABLE II (Continued)

JPL DATA — SUPPORT REMOVAL

| Time / Gage No. | 10:15 | 10:20 | 10:30 | 10:45 | 11:00 | 11:15 | 11:30 | 11:40 | 11:45 | 11:48 | 11:54 | 12:00 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | - 90 | - 93 | - 90 | - 86 | - 81 | - 74 | - 72 | - 69 | - 67 | - 58 | - 62 | - 58 |
| 4 | -171 | -171 | -171 | -164 | -164 | -157 | -154 | -157 | -154 | -154 | -154 | -150 |
| 5 | -211 | -209 | -208 | -206 | -208 | -201 | -201 | -201 | -201 | -203 | -201 | -201 |
| 6 | -149 | -161 | -156 | -156 | -156 | -151 | -151 | -151 | -151 | -144 | -153 | -151 |
| 7 | 167 | 157 | 164 | 169 | 173 | 180 | 182 | 184 | 184 | 191 | 189 | 194 |
| 8 | 150 | 155 | 155 | 157 | 157 | 162 | 161 | 164 | 166 | 164 | 168 | 168 |
| 9 | 46 | 39 | 42 | 44 | 51 | 56 | 53 | 58 | 58 | 65 | 55 | 62 |
| 10 | 64 | 69 | 69 | 73 | 73 | 76 | 81 | 80 | 83 | 80 | 85 | 85 |
| 11 | 170 | 166 | 170 | 172 | 172 | 177 | 181 | 183 | 183 | 190 | 188 | 190 |
| 12 | 135 | 137 | 137 | 135 | 137 | 135 | 137 | 137 | 137 | 132 | 139 | 137 |
| 13 | 138 | 138 | 136 | 138 | 138 | 140 | 138 | 142 | 140 | 138 | 145 | 140 |
| 14 | 157 | 148 | 150 | 155 | 157 | 162 | 168 | 168 | 164 | 173 | 161 | 171 |
| 15 | 182 | 173 | 173 | 184 | 191 | 200 | 195 | 199 | 199 | 209 | 202 | 213 |
| 16 | - 39 | - 35 | - 32 | - 30 | - 28 | - 28 | - 23 | - 21 | - 21 | - 21 | - 16 | - 16 |
| 17 | - 78 | - 90 | - 90 | - 81 | - 78 | - 62 | - 69 | - 67 | - 69 | - 55 | - 67 | - 53 |
| 18 | - 81 | - 81 | - 83 | - 75 | - 81 | - 79 | - 74 | - 74 | - 71 | - 74 | - 67 | - 69 |
| 19 | -183 | -183 | -181 | -176 | -176 | -171 | -169 | -169 | -169 | -167 | -164 | -164 |
| 20 | -215 | -214 | -215 | -214 | -214 | -212 | -214 | -211 | -211 | -207 | -209 | -209 |
| 21 | -143 | -150 | -145 | -143 | -138 | -127 | -129 | -126 | -126 | -117 | -124 | -117 |
| 22 | -140 | -135 | -133 | -133 | -131 | -135 | -126 | -126 | -124 | -126 | -126 | -123 |
| 23 | 152 | 152 | 155 | 157 | 157 | 164 | 161 | 163 | 163 | 163 | 165 | 168 |
| 24 | 168 | 168 | 173 | 177 | 180 | 187 | 188 | 191 | 191 | 193 | 193 | 198 |
| 25 | 32 | 26 | 30 | 32 | 39 | 53 | 44 | 46 | 46 | 55 | 49 | 60 |
| 26 | 34 | 37 | 39 | 37 | 37 | 39 | 39 | 39 | 41 | 39 | 46 | 46 |
| 27 | 167 | 174 | 176 | 178 | 183 | 185 | 189 | 194 | 196 | 196 | 196 | 196 |
| 28 | 170 | 170 | 172 | 174 | 174 | 181 | 183 | 190 | 192 | 194 | 197 | 201 |
| 29 | 116 | 111 | 116 | 123 | 127 | 146 | 134 | 143 | 143 | 152 | 150 | 157 |
| 30 | 133 | 135 | 133 | 133 | 131 | 128 | 135 | 139 | 139 | 139 | 142 | 142 |
| 31 | 140 | 140 | 140 | 142 | 142 | 147 | 147 | 151 | 154 | 151 | 156 | 154 |
| 32 | - 51 | - 49 | - 46 | - 46 | - 42 | - 37 | - 35 | - 32 | - 30 | - 30 | - 25 | - 25 |
| 33 | -100 | -104 | -104 | - 97 | - 90 | - 76 | - 74 | - 69 | - 74 | - 62 | - 67 | - 58 |
| 34 | - 78 | - 76 | - 76 | - 74 | - 76 | - 76 | - 71 | - 71 | - 69 | - 69 | - 69 | - 67 |
| 35 | 21 | 16 | 21 | 23 | 42 | - 49 | 0 | 2 | 0 | 9 | 7 | 16 |
| 36 | 63 | 65 | 70 | 72 | 101 | 63 | 0 | 2 | 4 | 4 | 6 | 6 |
| 37 | 146 | 135 | 151 | 164 | 175 | 209 | 179 | 188 | 193 | 213 | 202 | 255 |
| 38 | 93 | 102 | 107 | 104 | 102 | 95 | 111 | 115 | 117 | 117 | 122 | 117 |
| 39 | 99 | 105 | 108 | 107 | 108 | 103 | 118 | 125 | 125 | 121 | 130 | 118 |
| 40 | 108 | 104 | 106 | 108 | 116 | 129 | 131 | 135 | 134 | 143 | 141 | 147 |
| 41 | 89 | 89 | 95 | 95 | 97 | 103 | 99 | 103 | 105 | 107 | 109 | 116 |
| 42 | 116 | 108 | 112 | 122 | 133 | 162 | 135 | 141 | 141 | 158 | 147 | 189 |
| 43 | 146 | 141 | 150 | 159 | 168 | 190 | 174 | 183 | 190 | 206 | 194 | 228 |
| 44 | 40 | 44 | 44 | 44 | 42 | 40 | 46 | 51 | 55 | 55 | 57 | 57 |
| 45 | 49 | 51 | 54 | 51 | 51 | 47 | 58 | 60 | 65 | 62 | 65 | 62 |
| 46 | 76 | 74 | 76 | 82 | 90 | 105 | 99 | 105 | 105 | 113 | 111 | 124 |
| 47 | 111 | 115 | 113 | 115 | 111 | 111 | 117 | 127 | 132 | 136 | 140 | 136 |
| 48 | 97 | 93 | 99 | 107 | 116 | 137 | 118 | 126 | 134 | 143 | 134 | 162 |
| TC1 | | 65 | | 66 | 66 | | | 68 | 68 | 68 | 68 | 69 |
| TC2 | | 68 | | 68 | 68 | | | 70 | 70 | 70 | 70 | 69 |
| TC3 | 76 | | 76 | | | 81 | 79 | | | | | |
| TC4 | 81 | | 76 | | | 84 | 80 | | | | | |

to make sure the equipment is operating as required. The time-temperature-stress experiment began on the morning of 28 June 1965.

The gages were not rebalanced. Therefore, the initial strain on the gages was due to the dead weight of the structure, the roof insulation, and three fans in the equipment room. The previous roof-supporting system had been dismantled and removed from the site when this experiment was made and the ridge members of the roof had been welded at the equipment room connection making the gymnasium structurally complete.

The air conditioning equipment which kept JPL's equipment at a constant temperature failed near the end of the support removal test. This proved to be a handicap during the temperature scan experiment since several times a circuit breaker was opened by the air conditioner circuit which shut off the power to the automatic recording system. This is the reason that the data to be presented has several time gaps. The lack of a controlled temperature environment for the recording system caused the system to drift slightly. This drift has been corrected for in the data reduction procedure.

Dynamic data being taken the same day as this experiment were interrupted for short periods of time to permit the strain data to be recorded under static conditions. Gages 36 and 12T were mounted on the laboratory beams. Therefore they should have experienced no change in strain. Gage 35 data was irregular and was judged along with gages 22, 25, 31 and 37 to be faulty.

It can be seen by the strain data of gage 36 that during these two experiments the effect of temperature changes was much larger than the one micro-inch per inch per degree Fahrenheit expected. In order to determine the source of the disagreement the beam was laboratory tested at various increments of temperature increase above room temperature. With a new weld-on gage applied to replace gage 35, it was found that the apparent strain caused by temperature changes of the gages was as small as could be expected. Placing the beam and 100 feet of cable into the oven produced the same magnitude of apparent strain as experienced in the field test. Therefore, the tabulated JPL results of the experiments must be corrected to account for the apparent strain caused by changes in temperature of the lead cables.

It should be noted that temperature compensation is not required for the Caltech data because the cable lengths were only of the order of 10 feet and that each active gage had an identical dummy gage in the same balance bridge. By noting the apparent strains of 12T it can be seen that the changes with temperature throughout a test are within an acceptable range. It also shows that the strains from one day to the next cannot be directly compared. Table III gives a few readings on different days with the Caltech system. Table IV presents the data taken by JPL. It should be noted that these data have not been adjusted to account for the changes in temperature of the lead cables.

D. Horizontal Static Force.

It was thought that a measurement of the structural strains resulting from a known static horizontal force would give information needed to refine the analytical model of the structure. Such an experiment would also give a direct correlation between the member stresses and the dynamic experiments.

A maximum horizontal force component of 10, 000 pounds was determined to be appropriate. This force was about three per cent of the

# TABLE III

## CALTECH DATA - TEMPERATURE READINGS

| Time | June 23 | | June 28 | |
|---|---|---|---|---|
| | 10:12 | 10:26 | 3:01 | 3:16 |
| 1T | 17 | 9 | 53 | 58 |
| 2T | - 71 | - 75 | - 26 | - 23 |
| 3T | - 274 | - 281 | - 268 | - 265 |
| 4T | 846 | 903 | 1332 | 1329 |
| 5T | -1257 | -1253 | -1890 | -1890 |
| 6T | 612 | 596 | 540 | 552 |
| 7T | 15 | 11 | - 11 | - 8 |
| 8T | - 174 | - 177 | 733 | 747 |
| 9T | 566 | 572 | 843 | 842 |
| 10T | 593 | 587 | 782 | 784 |
| 11T | 186 | 190 | 174 | 171 |
| 12T | - 86 | - 81 | - 242 | - 242 |

TABLE IV

JPL DATA — TEMPERATURE SCAN

| Time | 9:00 | 9:30 | 10:00 | 12:20 | 12:30 | 13:00 | 13:30 | 14:00 | 14:30 | 15:00 |
|---|---|---|---|---|---|---|---|---|---|---|
| Gage No. | | | | | | | | | | |
| 3 | 125 | 148 | 168 | 248 | 252 | 263 | 272 | 282 | 289 | 289 |
| 4 | - 23 | - 7 | 0 | - 7 | 5 | 11 | 30 | 62 | 85 | 97 |
| 5 | -117 | -112 | -114 | -144 | -136 | -137 | -126 | -101 | - 85 | - 71 |
| 6 | - 7 | 2 | 9 | 81 | 68 | 60 | 42 | 33 | 19 | 0 |
| 7 | 395 | 408 | 421 | 490 | 495 | 500 | 500 | 517 | 523 | 525 |
| 8 | 411 | 406 | 401 | 371 | 380 | 385 | 401 | 425 | 449 | 463 |
| 9 | 234 | 239 | 252 | 330 | 327 | 328 | 326 | 333 | 327 | 322 |
| 10 | 177 | 184 | 186 | 161 | 180 | 189 | 216 | 249 | 272 | 391 |
| 11 | 317 | 321 | 327 | 390 | 389 | 397 | 401 | 407 | 415 | 419 |
| 12 | 162 | 155 | 148 | 137 | 131 | 130 | 137 | 149 | 160 | 167 |
| 13 | 365 | 362 | 355 | 330 | 332 | 328 | 342 | 368 | 389 | 401 |
| 14 | 314 | 323 | 334 | 385 | 385 | 385 | 383 | 388 | 294 | 394 |
| 15 | 411 | 427 | 437 | 495 | 504 | 512 | 525 | 540 | 555 | 560 |
| 16 | 78 | 84 | 84 | 64 | 73 | 80 | 103 | 137 | 165 | 181 |
| 17 | 103 | 119 | 137 | 204 | 205 | 206 | 213 | 225 | 228 | 223 |
| 18 | - 78 | - 69 | - 69 | - 94 | - 90 | - 80 | - 55 | - 21 | 7 | 21 |
| 19 | -152 | -145 | -136 | -145 | -139 | -134 | -116 | - 93 | - 80 | - 71 |
| 20 | -221 | -224 | -221 | -198 | -199 | -199 | -194 | -181 | -172 | -163 |
| 21 | -102 | -100 | - 92 | -102 | - 95 | - 97 | - 95 | - 83 | - 84 | - 84 |
| 22 | - | - | - | - | - | - | - | - | - | - |
| 23 | 216 | 221 | 225 | 248 | 247 | 246 | 258 | 274 | 291 | 293 |
| 24 | 243 | 248 | 250 | 259 | 265 | 271 | 287 | 310 | 336 | 348 |
| 25 | - | - | - | - | - | - | - | - | - | - |
| 26 | 34 | 34 | 30 | - 11 | - 5 | - 2 | 20 | 57 | 87 | 99 |
| 27 | 890 | 901 | 904 | 929 | 942 | 945 | 977 | 1011 | 1043 | 1063 |
| 28 | 200 | 212 | 204 | 150 | 165 | 173 | 214 | 265 | 311 | 336 |
| 29 | 235 | 248 | 259 | 326 | 332 | 336 | 350 | 364 | 367 | 376 |
| 30 | 210 | 206 | 190 | 103 | 113 | 114 | 146 | 188 | 227 | 248 |
| 31 | - | - | - | - | - | - | - | - | - | - |
| 32 | - 14 | - 9 | - 7 | 0 | 0 | 0 | 12 | 37 | 58 | 65 |
| 33 | - 93 | - 76 | - 60 | 16 | 16 | 25 | 35 | 51 | 58 | 63 |
| 34 | - 81 | - 74 | - 72 | - 72 | - 67 | - 65 | - 46 | - 21 | 0 | 9 |
| 35 | 55 | 65 | 76 | 140 | 137 | 138 | 138 | 143 | 144 | 148 |
| 36 | 145 | 157 | 161 | 153 | 164 | 172 | 206 | 246 | 280 | 299 |
| 37 | - | - | - | - | - | - | - | - | - | - |
| 38 | 35 | 40 | 40 | 40 | 53 | 55 | 102 | 146 | 191 | 209 |
| 39 | 31 | 40 | 42 | 49 | 63 | 65 | 116 | 164 | 209 | 231 |
| 40 | 115 | 144 | 165 | 240 | 252 | 265 | 293 | 325 | 346 | 369 |
| 41 | 65 | 77 | 79 | 81 | 90 | 92 | 131 | 175 | 207 | 222 |
| 42 | 163 | 203 | 224 | 299 | 303 | 319 | 342 | 378 | 349 | 370 |
| 43 | 128 | 170 | 201 | 318 | 329 | 352 | 394 | 349 | 462 | 491 |
| 44 | - 4 | 2 | 0 | - 11 | - 4 | - 4 | 37 | 81 | 117 | 132 |
| 45 | 16 | 20 | 18 | 4 | 11 | 7 | 40 | 82 | 85 | 98 |
| 46 | 110 | 140 | 160 | 250 | 249 | 265 | 288 | 324 | 335 | 358 |
| 47 | 61 | 99 | 109 | 128 | 140 | 133 | 185 | 239 | 195 | 201 |
| 48 | 96 | 129 | 158 | 273 | 274 | 296 | 327 | 353 | 362 | 389 |
| TC1 | 65 | 68 | 71 | 79 | 82 | 84 | 86 | 86 | 87 | 87 |
| TC2 | 80 | 83 | 85 | 86 | 87 | 87 | 87 | 87 | 86 | 85 |
| TC3 | 71 | 76 | 81 | 100 | 104 | 108 | 110 | 112 | 112 | 113 |
| TC4 | 88 | 95 | 99 | 103 | 104 | 105 | 103 | 107 | 103 | 101 |

TABLE IV (Continued)

JPL DATA — TEMPERATURE SCAN

| Time | 15:30 | 16:00 | 16:30 | 17:00 | 17:30 | 17:50 | 18:00 | 18:30 | 19:00 | 19:30 |
|---|---|---|---|---|---|---|---|---|---|---|
| Gage No. | | | | | | | | | | |
| 3 | 300 | 300 | 293 | 294 | 289 | 96 | 239 | 221 | 207 | 173 |
| 4 | 113 | 124 | 138 | 140 | 136 | - 28 | 104 | 127 | 126 | 122 |
| 5 | - 57 | - 46 | - 27 | - 28 | - 30 | -164 | - 46 | - 35 | - 34 | - 34 |
| 6 | 5 | - 2 | - 16 | - 19 | - 19 | -148 | - 47 | - 77 | - 91 | -125 |
| 7 | 540 | 533 | 533 | 541 | 539 | 404 | 504 | 493 | 482 | 452 |
| 8 | 469 | 485 | 501 | 511 | 523 | 399 | 509 | 541 | 541 | 546 |
| 9 | 329 | 322 | 310 | 313 | 309 | 193 | 275 | 259 | 248 | 211 |
| 10 | 311 | 316 | 334 | 339 | 349 | 193 | 325 | 367 | 359 | 359 |
| 11 | 425 | 437 | 437 | 449 | 449 | 332 | 425 | 412 | 395 | 365 |
| 12 | 169 | 176 | 185 | 183 | 192 | 136 | 189 | 202 | 203 | 203 |
| 13 | 409 | 416 | 430 | 433 | 442 | 362 | 439 | 458 | 459 | 468 |
| 14 | 400 | 400 | 395 | 408 | 403 | 295 | 375 | 361 | 356 | 330 |
| 15 | 572 | 577 | 572 | 585 | 576 | 429 | 539 | 530 | 512 | 482 |
| 16 | 199 | 210 | 224 | 236 | 238 | 118 | 214 | 235 | 235 | 230 |
| 17 | 234 | 230 | 225 | 226 | 210 | 104 | 166 | 143 | 128 | 96 |
| 18 | 39 | 48 | 62 | 58 | 64 | - 53 | 30 | 44 | 41 | 37 |
| 19 | - 71 | - 59 | - 52 | - 50 | - 50 | -168 | - 78 | - 66 | - 73 | - 93 |
| 20 | -153 | -149 | -139 | -140 | -144 | -233 | -168 | -173 | -180 | -199 |
| 21 | - 79 | - 74 | - 74 | - 60 | - 60 | -150 | - 79 | - 63 | - 58 | - 86 |
| 22 | - | - | - | - | - | - | - | - | - | - |
| 23 | 304 | 309 | 316 | 316 | 312 | 226 | 292 | 290 | 285 | 278 |
| 24 | 363 | 372 | 379 | 392 | 387 | 293 | 363 | 365 | 369 | 353 |
| 25 | - | - | - | - | - | - | - | - | - | - |
| 26 | 121 | 130 | 139 | 147 | 144 | 58 | 113 | 108 | 103 | 116 |
| 27 | 1075 | 1095 | 1109 | 1120 | 1125 | 1026 | 1097 | 1100 | 1080 | 1064 |
| 28 | 363 | 374 | 388 | 398 | 402 | 276 | 365 | 388 | 392 | 394 |
| 29 | 383 | 399 | 399 | 411 | 409 | 307 | 378 | 364 | 347 | 310 |
| 30 | 271 | 282 | 298 | 310 | 319 | 222 | 300 | 332 | 343 | 362 |
| 31 | - | - | - | - | - | - | - | - | - | - |
| 32 | 73 | 83 | 88 | 92 | 92 | 23 | 76 | 76 | 76 | 64 |
| 33 | 65 | 69 | 69 | 70 | 51 | - 44 | 9 | - 2 | - 14 | - 51 |
| 34 | 23 | 30 | 35 | 37 | 39 | - 54 | 14 | 23 | 18 | 14 |
| 35 | 146 | 152 | 146 | 150 | 141 | 65 | 109 | 88 | 71 | 37 |
| 36 | 318 | 328 | 345 | 350 | 350 | 264 | 320 | 328 | 319 | 311 |
| 37 | - | - | - | - | - | - | - | - | - | - |
| 38 | 226 | 253 | 268 | 280 | 284 | 188 | 254 | 274 | 266 | 261 |
| 39 | 251 | 273 | 291 | 301 | 305 | 206 | 271 | 286 | 277 | 266 |
| 40 | 373 | 385 | 383 | 384 | 367 | 260 | 310 | 287 | 261 | 219 |
| 41 | 242 | 251 | 259 | 262 | 260 | 162 | 219 | 229 | 221 | 206 |
| 42 | 374 | 376 | 376 | 375 | 349 | 227 | 283 | 258 | 233 | 191 |
| 43 | 490 | 515 | 512 | 511 | 496 | 358 | 426 | 411 | 370 | 308 |
| 44 | 150 | 165 | 176 | 183 | 185 | 98 | 153 | 175 | 169 | 169 |
| 45 | 120 | 125 | 136 | 138 | 138 | 61 | 112 | 135 | 131 | 136 |
| 46 | 355 | 364 | 359 | 356 | 339 | 251 | 290 | 265 | 238 | 190 |
| 47 | 224 | 228 | 245 | 262 | 262 | 171 | 223 | 236 | 225 | 209 |
| 48 | 382 | 401 | 397 | 394 | 381 | 295 | 326 | 296 | 261 | 200 |
| TC1 | 87 | 87 | 87 | 87 | 86 | 83 | 81 | 82 | 80 | 77 |
| TC2 | 85 | 85 | 84 | 85 | 84 | 81 | 79 | 80 | 78 | 75 |
| TC3 | 116 | 116 | 115 | 113 | 112 | 105 | 102 | 97 | 91 | 82 |
| TC4 | 104 | 98 | 92 | 88 | 85 | 78 | 75 | 74 | 73 | 68 |

TABLE IV (Continued)

JPL DATA — TEMPERATURE SCAN

| Time | 20:00 | 20:30 | 21:00 | 21:30 | 22:00 | 22:30 | 23:00 | 23:30 | 0:00 | 0:30 |
|---|---|---|---|---|---|---|---|---|---|---|
| Gage No. | | | | | | | | | | |
| 3 | 139 | 109 | 92 | 79 | 62 | 49 | 37 | 28 | 19 | 12 |
| 4 | 113 | 101 | 87 | 69 | 60 | 48 | 39 | 32 | 23 | 16 |
| 5 | - 39 | - 46 | - 55 | - 67 | - 69 | - 76 | - 80 | - 87 | - 92 | - 94 |
| 6 | -154 | -166 | -170 | -173 | -180 | -184 | -184 | -184 | -185 | -189 |
| 7 | 424 | 398 | 382 | 371 | 355 | 341 | 331 | 322 | 316 | 307 |
| 8 | 544 | 539 | 529 | 520 | 511 | 504 | 496 | 492 | 487 | 480 |
| 9 | 180 | 159 | 149 | 145 | 134 | 127 | 120 | 117 | 118 | 111 |
| 10 | 356 | 346 | 332 | 316 | 309 | 298 | 290 | 281 | 275 | 271 |
| 11 | 336 | 309 | 294 | 283 | 263 | 251 | 241 | 234 | 228 | 219 |
| 12 | 202 | 199 | 192 | 188 | 181 | 179 | 176 | 169 | 168 | 163 |
| 13 | 470 | 468 | 460 | 454 | 447 | 442 | 437 | 434 | 429 | 427 |
| 14 | 299 | 276 | 264 | 256 | 242 | 233 | 223 | 218 | 212 | 208 |
| 15 | 447 | 419 | 402 | 387 | 368 | 357 | 342 | 333 | 323 | 312 |
| 16 | 220 | 209 | 192 | 181 | 174 | 165 | 158 | 149 | 142 | 138 |
| 17 | 62 | 37 | 21 | 18 | 2 | - 9 | - 18 | - 23 | - 28 | - 37 |
| 18 | 28 | 16 | 5 | - 12 | - 18 | - 28 | - 34 | - 44 | - 46 | - 53 |
| 19 | -125 | -146 | -162 | -176 | -187 | -198 | -207 | -216 | -224 | -231 |
| 20 | -222 | -238 | -245 | -252 | -261 | -266 | -270 | -272 | -278 | -282 |
| 21 | -119 | -142 | -153 | -165 | -179 | -193 | -202 | -207 | -215 | -222 |
| 22 | - | - | - | - | - | - | - | - | - | - |
| 23 | 270 | 259 | 251 | 245 | 238 | 229 | 226 | 221 | 215 | 213 |
| 24 | 341 | 329 | 317 | 304 | 295 | 283 | 274 | 267 | 261 | 254 |
| 25 | - | - | - | - | - | - | - | - | - | - |
| 26 | 142 | 147 | 146 | 137 | 133 | 124 | 121 | 112 | 110 | 106 |
| 27 | 1043 | 1022 | 1006 | 992 | 978 | 965 | 956 | 947 | 944 | 939 |
| 28 | 395 | 384 | 370 | 352 | 336 | 318 | 303 | 292 | 282 | 268 |
| 29 | 279 | 259 | 249 | 242 | 229 | 217 | 210 | 205 | 201 | 190 |
| 30 | 374 | 379 | 374 | 363 | 354 | 347 | 337 | 330 | 322 | 318 |
| 31 | - | - | - | - | - | - | - | - | - | - |
| 32 | 42 | 27 | 18 | 9 | 2 | - 5 | - 9 | - 14 | - 21 | - 25 |
| 33 | - 91 | -118 | -134 | -146 | -162 | -172 | -181 | -185 | -195 | -200 |
| 34 | - 5 | - 19 | - 30 | - 42 | - 46 | - 53 | - 58 | - 65 | - 65 | - 70 |
| 35 | 7 | - 14 | - 21 | - 30 | - 39 | - 49 | - 55 | - 55 | - 65 | - 72 |
| 36 | 293 | 276 | 257 | 240 | 228 | 219 | 208 | 200 | 192 | 188 |
| 37 | - | - | - | - | - | - | - | - | - | - |
| 38 | 244 | 227 | 211 | 196 | 184 | 173 | 164 | 153 | 147 | 143 |
| 39 | 247 | 227 | 206 | 186 | 173 | 162 | 150 | 139 | 133 | 121 |
| 40 | 170 | 132 | 103 | 82 | 61 | 40 | 25 | 15 | 6 | - 8 |
| 41 | 188 | 170 | 150 | 134 | 121 | 111 | 100 | 92 | 84 | 80 |
| 42 | 139 | 103 | 76 | 55 | 34 | 13 | - 2 | - 11 | - 21 | - 38 |
| 43 | 238 | 193 | 164 | 140 | 111 | 89 | 71 | 60 | 42 | 31 |
| 44 | 159 | 146 | 130 | 114 | 104 | 93 | 81 | 75 | 71 | 64 |
| 45 | 130 | 114 | 105 | 89 | 80 | 71 | 65 | 56 | 49 | 45 |
| 46 | 144 | 105 | 77 | 57 | 36 | 17 | 6 | - 4 | - 17 | - 27 |
| 47 | 182 | 159 | 139 | 118 | 93 | 72 | 61 | 51 | 49 | 40 |
| 48 | 130 | 88 | 63 | 48 | 25 | 10 | - 2 | - 8 | - 19 | - 29 |
| TC1 | 74 | 70 | 68 | 66 | 64 | 62 | 61 | 60 | 59 | 58 |
| TC2 | 74 | 71 | 69 | 67 | 65 | 64 | 62 | 61 | 60 | 59 |
| TC3 | 69 | 63 | 60 | 59 | 57 | 55 | 54 | 54 | 53 | 52 |
| TC4 | 65 | 63 | 61 | 59 | 58 | 56 | 55 | 55 | 54 | 53 |

TABLE IV (Continued)

JPL DATA — TEMPERATURE SCAN

| Time | 1:00 | 2:00 | 3:00 | 9:00 | 9:30 | 10:00 | 10:30 | 11:00 | 11:30 | 12:00 |
|---|---|---|---|---|---|---|---|---|---|---|
| Gage No. | | | | | | | | | | |
| 3 | 9 | - 2 | 5 | 86 | 124 | 146 | 164 | 196 | 233 | 254 |
| 4 | 14 | 5 | - 7 | - 12 | 2 | 23 | 41 | 51 | 64 | 78 |
| 5 | -101 | -103 | -110 | - 99 | -101 | - 94 | - 82 | - 87 | - 87 | - 83 |
| 6 | -183 | -182 | -175 | - 19 | - 9 | - 14 | - 12 | 2 | 16 | 16 |
| 7 | 305 | 297 | 292 | 365 | 388 | 402 | 415 | 439 | 473 | 490 |
| 8 | 479 | 470 | 464 | 429 | 415 | 416 | 420 | 423 | 422 | 427 |
| 9 | 113 | 113 | 115 | 224 | 239 | 239 | 245 | 267 | 296 | 306 |
| 10 | 267 | 259 | 249 | 199 | 202 | 217 | 230 | 237 | 246 | 256 |
| 11 | 217 | 212 | 207 | 288 | 305 | 313 | 310 | 331 | 358 | 375 |
| 12 | 163 | 160 | 155 | 158 | 144 | 139 | 132 | 128 | 128 | 128 |
| 13 | 425 | 419 | 414 | 406 | 392 | 393 | 399 | 393 | 388 | 386 |
| 14 | 206 | 200 | 200 | 282 | 298 | 299 | 310 | 326 | 346 | 361 |
| 15 | 314 | 299 | 292 | 376 | 397 | 409 | 424 | 451 | 486 | 506 |
| 16 | 136 | 126 | 119 | 76 | 75 | 89 | 103 | 107 | 119 | 128 |
| 17 | - 35 | - 39 | - 41 | 81 | 108 | 113 | 126 | 147 | 177 | 193 |
| 18 | - 55 | - 62 | - 71 | - 78 | - 69 | - 55 | - 41 | - 39 | - 32 | - 21 |
| 19 | -231 | -237 | -237 | 194 | -175 | -162 | -148 | -139 | -123 | -109 |
| 20 | -281 | -284 | -285 | -234 | -237 | -236 | -228 | -226 | -217 | -201 |
| 21 | -222 | -230 | -230 | -173 | -151 | -146 | -137 | -130 | -111 | -116 |
| 22 | - | - | - | - | - | - | - | - | - | - |
| 23 | 213 | 205 | 205 | 227 | 223 | 224 | 232 | 240 | 251 | 258 |
| 24 | 254 | 244 | 239 | 226 | 234 | 237 | 248 | 257 | 273 | 285 |
| 25 | - | - | - | - | - | - | - | - | - | - |
| 26 | 104 | 96 | 91 | 34 | 32 | 43 | 53 | 59 | 66 | 71 |
| 27 | 936 | 921 | 915 | 934 | 929 | 949 | 965 | 986 | 1004 | 1024 |
| 28 | 262 | 245 | 233 | 158 | 178 | 194 | 207 | 221 | 239 | 251 |
| 29 | 192 | 185 | 184 | 254 | 258 | 256 | 269 | 288 | 315 | 334 |
| 30 | 311 | 301 | 293 | 203 | 190 | 188 | 185 | 183 | 183 | 183 |
| 31 | - | - | - | - | - | - | - | - | - | - |
| 32 | - 23 | - 30 | - 30 | - 28 | - 25 | - 18 | - 9 | 0 | 11 | 21 |
| 33 | -200 | -207 | -206 | -116 | - 95 | - 86 | - 62 | - 44 | - 12 | 7 |
| 34 | - 72 | - 74 | - 79 | - 86 | - 83 | - 74 | - 60 | - 53 | - 46 | - 35 |
| 35 | - 67 | - 72 | - 69 | 14 | 20 | 23 | 35 | 53 | 78 | 88 |
| 36 | 184 | 173 | 166 | 137 | 151 | 170 | 189 | 204 | 218 | 236 |
| 37 | - | - | - | - | - | - | - | - | - | - |
| 38 | 136 | 127 | 118 | 31 | 33 | 62 | 71 | 86 | 100 | 120 |
| 39 | 117 | 108 | 96 | 9 | 27 | 58 | 74 | 99 | 116 | 143 |
| 40 | - 11 | - 23 | - 29 | 42 | 98 | 124 | 167 | 201 | 249 | 283 |
| 41 | 74 | 65 | 58 | 50 | 69 | 94 | 115 | 136 | 152 | 167 |
| 42 | - 40 | - 53 | - 57 | 80 | 142 | 168 | 218 | 256 | 306 | 323 |
| 43 | 25 | 9 | 2 | 60 | 117 | 164 | 219 | 271 | 325 | 368 |
| 44 | 62 | 51 | 46 | - 2 | 9 | 24 | 37 | 51 | 61 | 75 |
| 45 | 40 | 33 | 27 | - 11 | - 2 | 11 | 24 | 33 | 42 | 56 |
| 46 | - 2[illegible] | - 40 | - 42 | 36 | 79 | 104 | 142 | 175 | 219 | 249 |
| 47 | 38 | 34 | 36 | - 19 | 25 | 65 | 91 | 120 | 145 | 190 |
| 48 | - 2[illegible] | - 38 | - 38 | 57 | 96 | 127 | 175 | 215 | 265 | 299 |
| TC1 | 58 | 56 | 55 | 58 | 62 | 64 | 67 | 70 | 73 | 76 |
| TC2 | 58 | 57 | 56 | 62 | 69 | 74 | 79 | 81 | 84 | 85 |
| TC3 | 52 | 52 | 53 | 69 | 73 | 77 | 88 | 89 | 95 | 101 |
| TC4 | 53 | 53 | 53 | 80 | 90 | 92 | 100 | 103 | 106 | 107 |

weight of the structure and there was some concern that a larger force might produce local yielding at the load application point of the structure.

The force was applied with the hydraulic winch of a tank recovery vehicle through a 5/8-inch diameter steel rope. This vehicle and the steel rope can be seen in Fig. 5. The connection to the structure was made by placing a steel choker rope around a horizontal steel beam temporarily spanning between two vertical truss members at the north major axis four inches above the concrete floor of the equipment room. The load cell and a hydraulic cylinder were connected between the end of the 5/8-inch diameter steel rope and the winch cable.

The loading system was able to maintain the applied load within a decrease of about 200 pounds during the time required to obtain a data scan. The applied force was not exactly in a horizontal direction. The components of the measured force are: horizontal components of 0.993 in the northerly direction and 0.017 in the easterly direction, and the vertical component of 0.133 in the downward direction.

The only problem of consequence encountered during this experiment was caused by the tendency of the steel rope to unwind as the tension in the rope increased. Since the least resistance to the rotation of the cable occurred at the end of the winch cable, the load cell and the hydraulic cylinder were rotated with the steel rope. This in itself is not a problem, but the electrical wire connecting the load cell to the recorder also wraps around the steel rope and in one instance became jammed between the load cell and hydraulic cylinder causing the bolt connection to loosen and finally causing the loosened bolt to cut the electrical wire. After repairing

| Time | July 10 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 9:00 | 9:15 | 10:35 | 10:37 | 10:46 | 10:57 | 11:15 | 11:20 | 1:45 | 1:53 | 2:00 | 2:06 |
| 1T | 383 | 388 | 400 | 405 | 403 | 400 | 401 | 401 | 409 | 403 | 403 | 403 |
| 2T | 548 | 545 | 559 | 562 | 560 | 560 | 562 | 565 | 555 | 550 | 548 | 548 |
| 3T | - 409 | - 400 | - 381 | - 377 | - 379 | - 379 | - 375 | - 375 | - 379 | - 381 | - 381 | - 385 |
| 4T | 3406 | 3406 | 3395 | 3395 | 3395 | 3393 | 3400 | 3400 | 3409 | 3400 | 3406 | 3400 |
| 5T | -4380 | -4420 | -4415 | -4425 | -4430 | -4406 | -4430 | -4430 | -4460 | -4450 | -4470 | -4460 |
| 6T | 558 | 554 | 558 | 562 | 530 | 562 | 568 | 568 | 577 | 573 | 573 | 575 |
| 7T | - 396 | - 400 | -405 | - 405 | - 411 | - 409 | - 413 | - 415 | - 433 | - 437 | - 431 | - 431 |
| 8T | 3226 | 3140 | 3545 | 3850 | 3980 | 4140 | 4300 | 4330 | 5440 | 5440 | 5470 | 5450 |
| 9T | 1827 | 1820 | 1823 | 1823 | 1827 | 1828 | 1831 | 1835 | 1849 | 1849 | 1840 | 1845 |
| 10T | 1417 | 1425 | 1468 | 1468 | 1472 | 1475 | 1482 | 1483 | 1487 | 1497 | 1497 | 1494 |
| 11T | 184 | 180 | 150 | 150 | 146 | 142 | 140 | 144 | 142 | 146 | 142 | 142 |
| 12T | -1580 | -1582 | -1590 | -1586 | -1588 | -1592 | -1590 | -1593 | -1601 | -1598 | -1602 | -1602 |
| Force | 0 | 601 | 3733 | 3507 | 4100 | 4551 | 4591 | 4591 | 201 | 2153 | 5262 | 5262 |

TABLE V

CALTECH DATA - HORIZONTAL STATIC FORCE

| Time | July 10 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2:15 | 2:25 | 3:06 | 3:17 | 3:24 | 3:37 | 3:47 | 3:52 | 3:58 | 4:07 | 4:15 |
| 1T | 403 | 407 | 403 | 398 | 407 | 401 | 401 | 405 | 403 | 407 | 401 |
| 2T | 545 | 544 | 544 | 540 | 541 | 539 | 541 | 540 | 536 | 539 | 539 |
| 3T | - 385 | - 385 | - 390 | - 388 | - 388 | - 388 | - 390 | - 390 | - 390 | - 390 | - 394 |
| 4T | 3400 | 3406 | 3406 | 3400 | 3400 | 3400 | 3406 | 3406 | 3400 | 3406 | 3400 |
| 5T | -4470 | -4470 | -4460 | -4460 | -4470 | -4490 | -4490 | -4485 | -4470 | -4470 | -4470 |
| 6T | 577 | 573 | 581 | 575 | 579 | 575 | 575 | 585 | 581 | 573 | 573 |
| 7T | - 431 | - 437 | - 440 | - 439 | - 435 | - 437 | - 445 | - 437 | - 437 | - 443 | - 445 |
| 8T | 5485 | 5490 | 5500 | 5500 | 5520 | 5540 | 5565 | 5565 | 5575 | 5590 | 5600 |
| 9T | 1843 | 1856 | 1858 | 1858 | 1858 | 1854 | 1863 | 1863 | 1863 | 1870 | 1872 |
| 10T | 1492 | 1497 | 1500 | 1494 | 1490 | 1492 | 1497 | 1492 | 1490 | 1492 | 1492 |
| 11T | 140 | 146 | 154 | 152 | 148 | 152 | 157 | 154 | 154 | 156 | 157 |
| 12T | -1602 | -1602 | -1602 | -1602 | -1600 | -1605 | -1605 | -1605 | -1602 | -1602 | -1602 |
| Force | 5993 | 7315 | 0 | 5121 | 7556 | 6748 | 2580 | 6754 | 8101 | 1260 | 20 |

TABLE V (Continued)

CALTECH DATA - HORIZONTAL STATIC FORCE

TABLE VI

JPL DATA — HORIZONTAL FORCE

| Time | 9:10 | 10:21 | 10:41 | 10:43 | 10:54 | 11:04 | 11:20 | 13:50 | 13:58 | 14:05 | 14:12 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Force | 0 | 601 | 3733 | 3507 | 4100 | 4551 | 4591 | 201 | 2153 | 5262 | 5993 |
| Gage No. | | | | | | | | | | | |
| 3 | 5 | 74 | 85 | 88 | 99 | 103 | 126 | 210 | 218 | 213 | 208 |
| 4 | 2 | 19 | 30 | 26 | 32 | 42 | 46 | 91 | 100 | 105 | 111 |
| 5 | 2 | 5 | 16 | 9 | 14 | 23 | 25 | 39 | 46 | 51 | 53 |
| 6 | 2 | 49 | 55 | 56 | 63 | 65 | 76 | 135 | 130 | 121 | 118 |
| 7 | 0 | 53 | 55 | 58 | 64 | 67 | 83 | 162 | 169 | 166 | 171 |
| 8 | - | - | - | - | - | - | - | - | - | - | - |
| 9 | 5 | 58 | 62 | 60 | 67 | 69 | 85 | 168 | 171 | 159 | 159 |
| 10 | - 2 | 5 | 12 | 5 | 9 | 16 | 18 | 37 | 44 | 56 | 60 |
| 11 | 2 | 55 | 66 | 64 | 69 | 80 | 87 | 161 | 166 | 168 | 172 |
| 12 | - 7 | - 18 | - 23 | - 25 | - 25 | - 25 | - 32 | - 39 | - 35 | - 25 | - 23 |
| 13 | 0 | - 18 | - 18 | - 11 | - 18 | - 11 | - 11 | - 30 | - 21 | - 23 | - 9 |
| 14 | 0 | 25 | 34 | 37 | 44 | 48 | 64 | 116 | 118 | 116 | 115 |
| 15 | 5 | 66 | 73 | 76 | 85 | 87 | 103 | 181 | 193 | 190 | 195 |
| 16 | 0 | - 7 | - 2 | - 7 | - 5 | 0 | 0 | 23 | 32 | 44 | 46 |
| 17 | 7 | 82 | 91 | 96 | 105 | 105 | 125 | 204 | 212 | 202 | 202 |
| 18 | 5 | 25 | 32 | 27 | 34 | 43 | 46 | 62 | 71 | 78 | 82 |
| 19 | 2 | 52 | 63 | 59 | 66 | 72 | 72 | 100 | 110 | 107 | 111 |
| 20 | 5 | 27 | 30 | 25 | 32 | 32 | 41 | 73 | 78 | 78 | 80 |
| 21 | 0 | 48 | 53 | 53 | 60 | 57 | 66 | 92 | 97 | 92 | 94 |
| 22 | - | - | - | - | - | - | - | - | - | - | - |
| 23 | 0 | 9 | 18 | 14 | 18 | 23 | 23 | 51 | 58 | 62 | 64 |
| 24 | 0 | 2 | 7 | 7 | 14 | 14 | 23 | 53 | 62 | 64 | 73 |
| 25 | - | - | - | - | - | - | - | - | - | - | - |
| 26 | 0 | 9 | 14 | 9 | 11 | 20 | 20 | 18 | 23 | 32 | 32 |
| 27 | 0 | - 14 | - 9 | - 9 | - 7 | - 2 | 2 | 46 | 58 | 69 | 76 |
| 28 | 2 | 14 | 16 | 14 | 18 | 20 | 23 | 43 | 57 | 66 | 73 |
| 29 | 5 | 30 | 30 | 28 | 34 | 37 | 44 | 125 | 132 | 131 | 138 |
| 30 | - 2 | - 23 | - 25 | - 32 | - 32 | - 30 | - 34 | - 69 | - 60 | - 50 | - 46 |
| 31 | - | - | - | - | - | - | - | - | - | - | - |
| 32 | 0 | 5 | 11 | 7 | 14 | 18 | 23 | 53 | 57 | 57 | 83 |
| 33 | 2 | 67 | 78 | 78 | 85 | 92 | 103 | 196 | 196 | 198 | 60 |
| 34 | 0 | 9 | 16 | 12 | 16 | 23 | 25 | 46 | 51 | 58 | 198 |
| 35 | - | - | - | - | - | - | - | - | - | - | - |
| 36 | - | - | - | - | - | - | - | - | - | - | - |
| 37 | - | - | - | - | - | - | - | - | - | - | - |
| 38 | - 2 | - 13 | 4 | - 4 | 9 | 11 | 18 | 60 | 76 | 93 | 100 |
| 39 | - 2 | - 7 | 18 | 13 | 25 | 33 | 38 | 94 | 112 | 128 | 132 |
| 40 | 8 | 103 | 126 | 126 | 139 | 151 | 168 | 291 | 302 | 299 | 301 |
| 41 | 2 | 40 | 50 | 46 | 55 | 65 | 76 | 106 | 116 | 123 | 131 |
| 42 | 17 | 166 | 178 | 180 | 182 | 207 | 228 | 317 | 326 | 317 | 323 |
| 43 | 13 | 118 | 140 | 140 | 153 | 177 | 200 | 344 | 362 | 364 | 370 |
| 44 | 4 | 7 | 18 | 13 | 20 | 26 | 29 | 49 | 60 | 71 | 75 |
| 45 | 2 | 13 | 27 | 20 | 27 | 31 | 38 | 54 | 65 | 74 | 78 |
| 46 | 4 | 88 | 105 | 109 | 118 | 132 | 147 | 263 | 270 | 270 | 271 |
| 47 | 6 | 40 | 60 | 56 | 64 | 75 | 85 | 142 | 163 | 177 | 185 |
| 48 | 8 | 96 | 112 | 117 | 123 | 139 | 162 | 297 | 306 | 303 | 309 |
| TC1 | 59 | 63 | 65 | 64 | 66 | 66 | 68 | 83 | 83 | 83 | 84 |
| TC2 | 60 | 63 | 66 | 66 | 66 | 67 | 69 | 82 | 82 | 83 | 83 |
| TC3 | 71 | 82 | 84 | 84 | 85 | 87 | 91 | 112 | 113 | 114 | 114 |
| TC4 | 69 | 97 | 100 | 100 | 102 | 103 | 108 | 112 | 110 | 108 | 106 |

TABLE VI (Continued)

JPL DATA — HORIZONTAL FORCE

| Time | 14:18 | 15:10 | 15:24 | 15:29 | 15:43 | 15:53 | 15:58 | 16:04 | 16:13 | 16:21 |
|---|---|---|---|---|---|---|---|---|---|---|
| Force | 7315 | 0 | 5121 | 7556 | 6748 | 2580 | 6754 | 8101 | 1260 | 20 |
| Gage No. | | | | | | | | | | |
| 3 | 215 | 208 | 219 | 215 | 206 | 210 | 203 | 205 | 205 | 205 |
| 4 | 114 | 130 | 134 | 137 | 139 | 139 | 137 | 139 | 139 | 139 |
| 5 | 55 | 69 | 76 | 78 | 83 | 83 | 85 | 88 | 85 | 85 |
| 6 | 118 | 97 | 95 | 90 | 79 | 93 | 88 | 79 | 86 | 90 |
| 7 | 175 | 178 | 180 | 180 | 176 | 180 | 173 | 175 | 175 | 175 |
| 8 | - | - | - | - | - | - | - | - | - | - |
| 9 | 157 | 157 | 149 | 145 | 141 | 145 | 133 | 131 | 140 | 140 |
| 10 | 63 | 88 | 90 | 93 | 98 | 102 | 97 | 102 | 106 | 107 |
| 11 | 176 | 179 | 192 | 192 | 181 | 187 | 179 | 192 | 194 | 192 |
| 12 | - 16 | 0 | 2 | 5 | 9 | 12 | 12 | 14 | 14 | 16 |
| 13 | - 9 | - 7 | 7 | - 2 | 16 | 2 | 0 | 9 | 5 | 5 |
| 14 | 120 | 120 | 124 | 125 | 116 | 124 | 122 | 120 | 124 | 124 |
| 15 | 202 | 206 | 206 | 208 | 207 | 206 | 204 | 203 | 203 | 203 |
| 16 | 53 | 80 | 89 | 90 | 97 | 96 | 99 | 103 | 105 | 105 |
| 17 | 204 | 199 | 197 | 195 | 186 | 185 | 183 | 181 | 185 | 183 |
| 18 | 87 | 103 | 112 | 112 | 115 | 117 | 114 | 117 | 119 | 117 |
| 19 | 114 | 127 | 122 | 118 | 123 | 122 | 116 | 122 | 122 | 123 |
| 20 | 80 | 92 | 87 | 87 | 87 | 91 | 87 | 87 | 94 | 96 |
| 21 | 83 | 106 | 101 | 99 | 97 | 106 | 97 | 94 | 108 | 106 |
| 22 | - | - | - | - | - | - | - | - | - | - |
| 23 | 198 | 71 | 76 | 78 | 78 | 78 | 76 | 80 | 76 | 76 |
| 24 | 64 | 87 | 101 | 96 | 101 | 94 | 96 | 105 | 103 | 98 |
| 25 | - | - | - | - | - | - | - | - | - | - |
| 26 | 41 | 50 | 57 | 57 | 62 | 62 | 59 | 66 | 59 | 64 |
| 27 | 78 | 94 | 103 | 106 | 111 | 113 | 115 | 119 | 117 | 117 |
| 28 | 75 | 105 | 121 | 123 | 126 | 128 | 128 | 132 | 130 | 130 |
| 29 | 138 | 145 | 149 | 152 | 150 | 149 | 147 | 149 | 149 | 142 |
| 30 | - 41 | - 16 | - 2 | 2 | 7 | 5 | 9 | 14 | 11 | 14 |
| 31 | - | - | - | - | - | - | - | - | - | - |
| 32 | 62 | 69 | 66 | 66 | 67 | 69 | 64 | 66 | 71 | 71 |
| 33 | 198 | 200 | 200 | 198 | 194 | 198 | 191 | 188 | 193 | 188 |
| 34 | 64 | 81 | 83 | 83 | 85 | 87 | 85 | 90 | 90 | 92 |
| 35 | - | - | - | - | - | - | - | - | - | - |
| 36 | - | - | - | - | - | - | - | - | - | - |
| 37 | - | - | - | - | - | - | - | - | - | - |
| 38 | 104 | 133 | 139 | 144 | 151 | 157 | 155 | 164 | 168 | 168 |
| 39 | 137 | 168 | 174 | 177 | 184 | 185 | 186 | 192 | 192 | 194 |
| 40 | 303 | 315 | 315 | 311 | 312 | 306 | 305 | 302 | 304 | 300 |
| 41 | 135 | 150 | 154 | 156 | 158 | 160 | 156 | 158 | 158 | 160 |
| 42 | 325 | 325 | 327 | 319 | 317 | 312 | 310 | 301 | 304 | 299 |
| 43 | 374 | 387 | 391 | 392 | 393 | 389 | 383 | 382 | 387 | 384 |
| 44 | 79 | 99 | 108 | 112 | 113 | 114 | 112 | 114 | 114 | 117 |
| 45 | 82 | 102 | 109 | 111 | 114 | 116 | 114 | 116 | 116 | 116 |
| 46 | 275 | 284 | 283 | 278 | 280 | 275 | 273 | 271 | 273 | 269 |
| 47 | 198 | 225 | 231 | 235 | 236 | 235 | 233 | 235 | 235 | 237 |
| 48 | 313 | 319 | 319 | 315 | 320 | 314 | 311 | 306 | 312 | 312 |
| TC1 | 84 | 86 | 86 | 86 | 86 | 86 | 86 | 86 | 86 | 86 |
| TC2 | 83 | 83 | 84 | 83 | 83 | 83 | 83 | 83 | 83 | 83 |
| TC3 | 115 | 114 | 113 | 114 | 113 | 113 | 112 | 112 | 111 | 112 |
| TC4 | 106 | 101 | 101 | 100 | 97 | 95 | 94 | 93 | 92 | 90 |

the electrical wire, precautions were taken to make sure that the electrical wire wrapped only around the steel rope.

The results obtained from this experiment follow in Tables V and VI. It should be noted that the strain gage circuits monitored by JPL had been rebalanced before running this experiment.

## DYNAMIC INVESTIGATION

It has been the good fortune of the writer that much effort has previously been made by the faculty and students at the California Institute of Technology to establish a dynamic measurement system for the dynamic response of full-scale civil engineering structures. The system used in this investigation has been used for many full-scale and reduced scale studies of the dynamic response of structures such as earth dams and buildings. The measurement system consists of the transducers, the amplifiers, and the recorder. In the following, the elements of the instrumentation system will be discussed in that order.

### Instrumentation

The accelerometers used were Statham ±2g accelerometers, type A5-2-350, serial numbers 12133, 12134, 11181, 11182 and 12122. These accelerometers have an undamped natural frequency of 100 cps with a liquid damping of 0.7 ± 0.1 fraction of critical damping and, therefore, are effectively linear at least up to 30 cps. The accelerometers were not frequency calibrated by the writer absolutely, but were cross calibrated in the frequency range used with a maximum disagreement of about 2 per cent. The static ±1g method of calibration by rotating the transducer through ±90 degrees was used before and after each test.

An attempt to use a JPL balanced strain gage bridge as a transducer to give the dynamic strain was made without significant results because the strains were too low.

A Sanborn dual channel carrier-amplifier recorder Model No. 321-406368 was used to record man-excited free vibrations of the structure. The man-excited vibration was large enough to determine the lowest natural frequency of the structure in the two major directions and to estimate the amount of damping in the structure at small vibrations. The results obtained on 24 June 1965 were: in the North-South direction, $f_n = 3.50$ cps, damping of 1.29% at a deflection of 0.0007 inches and in the East-West direction, $f_n = 2.44$ cps, damping of 0.55% at a deflection of 0.0029 inches. Figure 15 shows an example of the type of response recorded from man-excited vibrations.

The system used for a majority of the experimental work was originally used for testing a reinforced concrete reservoir intake tower. Because of the low amplifier noise generation, it was also used with more sensitive accelerometers for dynamic testing of earth dams. This system consisted of the William Miller Type C-3 carrier-amplifiers with a light beam galvanometer recording oscillograph. The amplifier provides a 3000 cps carrier bridge excitation adjustable up to 10 volts. The accelerometers were balanced very easily with this amplifier with the exception of the accelerometers placed in a vertical position with a cable length of more than 150 feet. A slight modification of the balancing circuit of the amplifier satisfactorily extended the balance range. Six carrier-amplifiers with one power supply were in one unit, which was

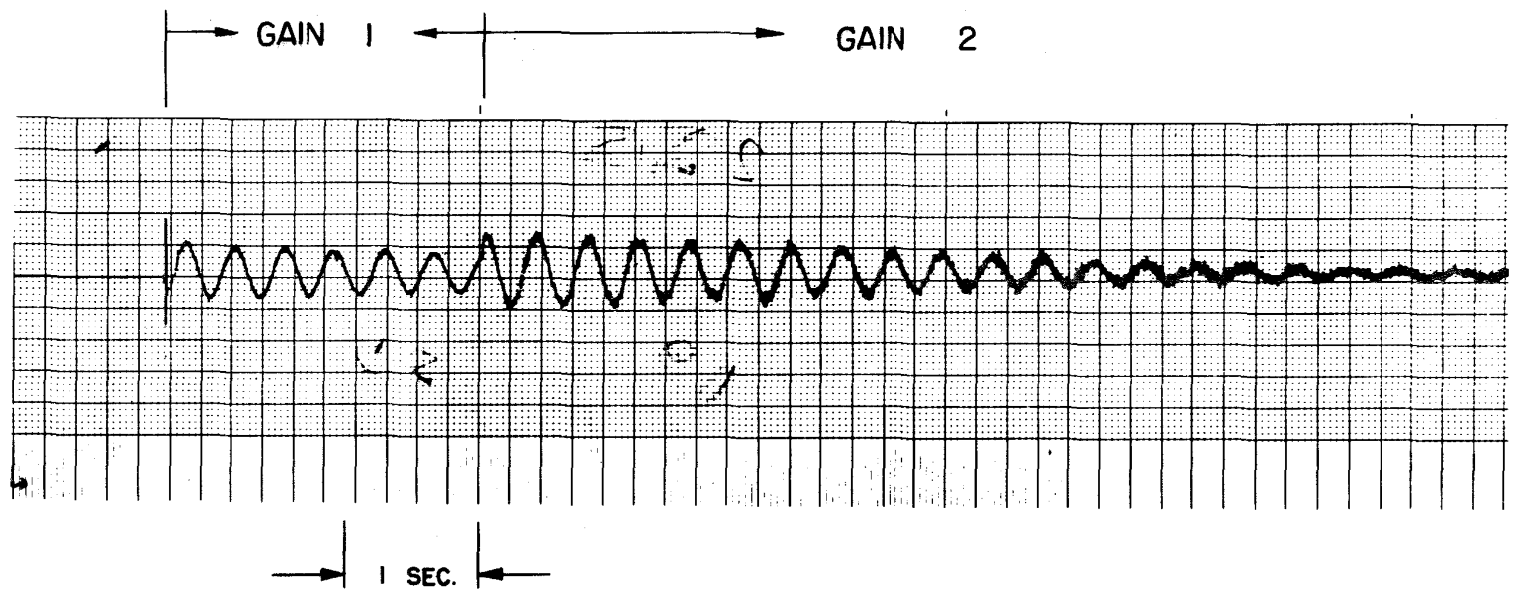



Fig. 15. Man-excited vibration.

sufficient for this experiment. The amplifiers were remarkably stable for long periods of time.

The Minneapolis-Honeywell Visicorder recording oscillograph is a light beam galvanometer type which records on light-sensitive paper. Four type M40-120A galvanometers, 40 cps natural frequency, were used for most of the data recording with two type M100-120A galvanometers, 100 cps natural frequency, used for one data channel and for an analysis of the ambient vibration.

Ideally, the maximum reading error of the oscillograph records was ±0.1 line in 10 lines or ±1 per cent of the reading. However, the ambient high frequency components superimposed on the forced vibration frequency record increased the possible error in certain instances. Several examples of typical acceleration records are given in Figs. 16 and 17. Figure 16 shows the condition when the high frequency signal can cause relatively large reading errors and Fig. 17 shows the condition where this signal is easily eliminated by eye. The single amplitude ambient acceleration will be indicated on the figures of the frequency response curves for the structure.

## Force Generator System

The mechanical force generator* consists of a pair of counter-rotating eccentric counter-balanced baskets located on a common vertical shaft and driven in opposite directions by a chain drive system. When the baskets have equally distributed additional weights, a rectilinear sinusoidally varying horizontal inertia force is generated. The direction of the

*Hudson, D. E., "Synchronized Vibration Generators for Dynamic Tests of Full-Scale Structures," Earthquake Engineering Research Laboratory, California Institute of Technology, November 1962.

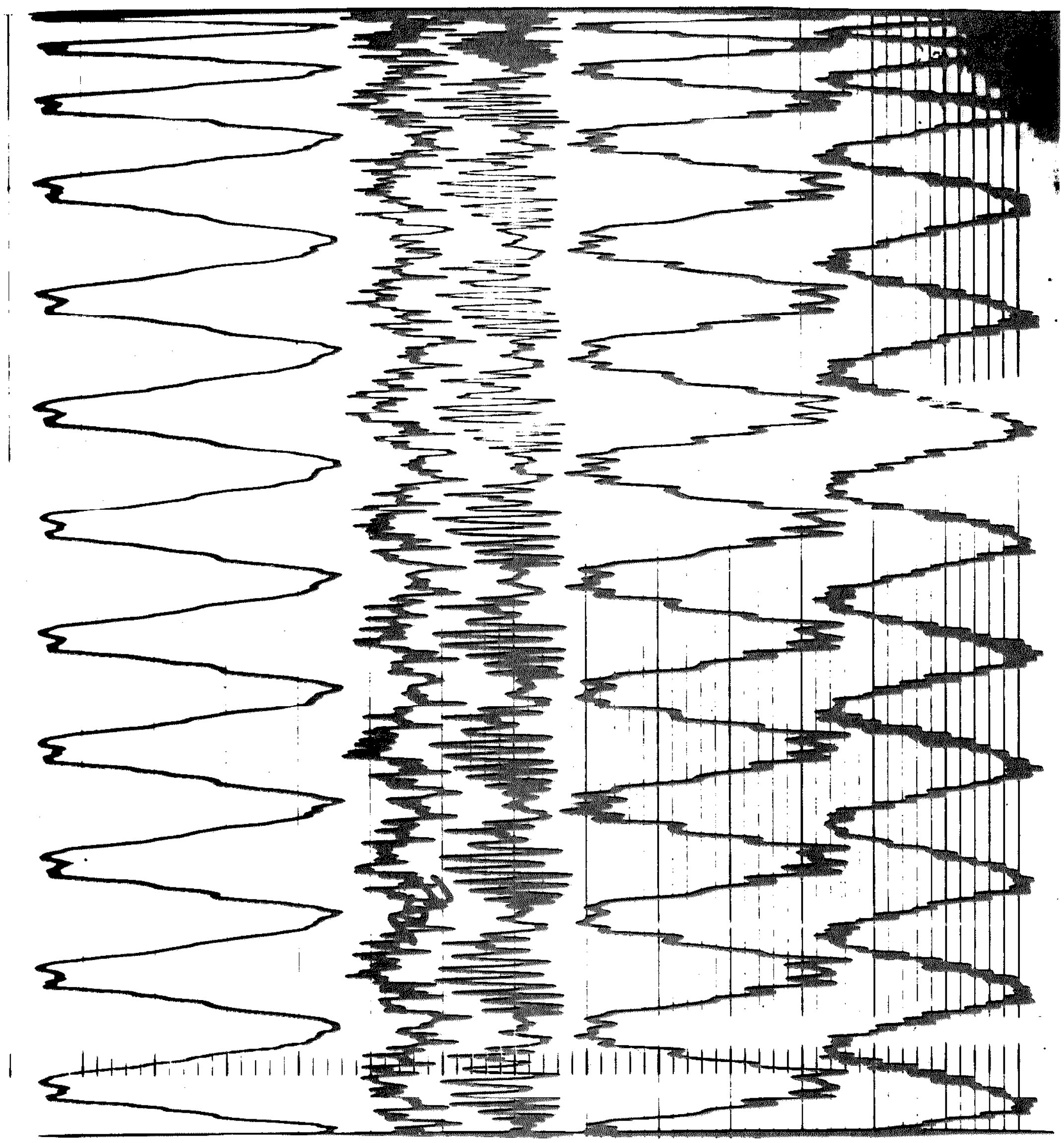


Fig. 16. Typical acceleration record.

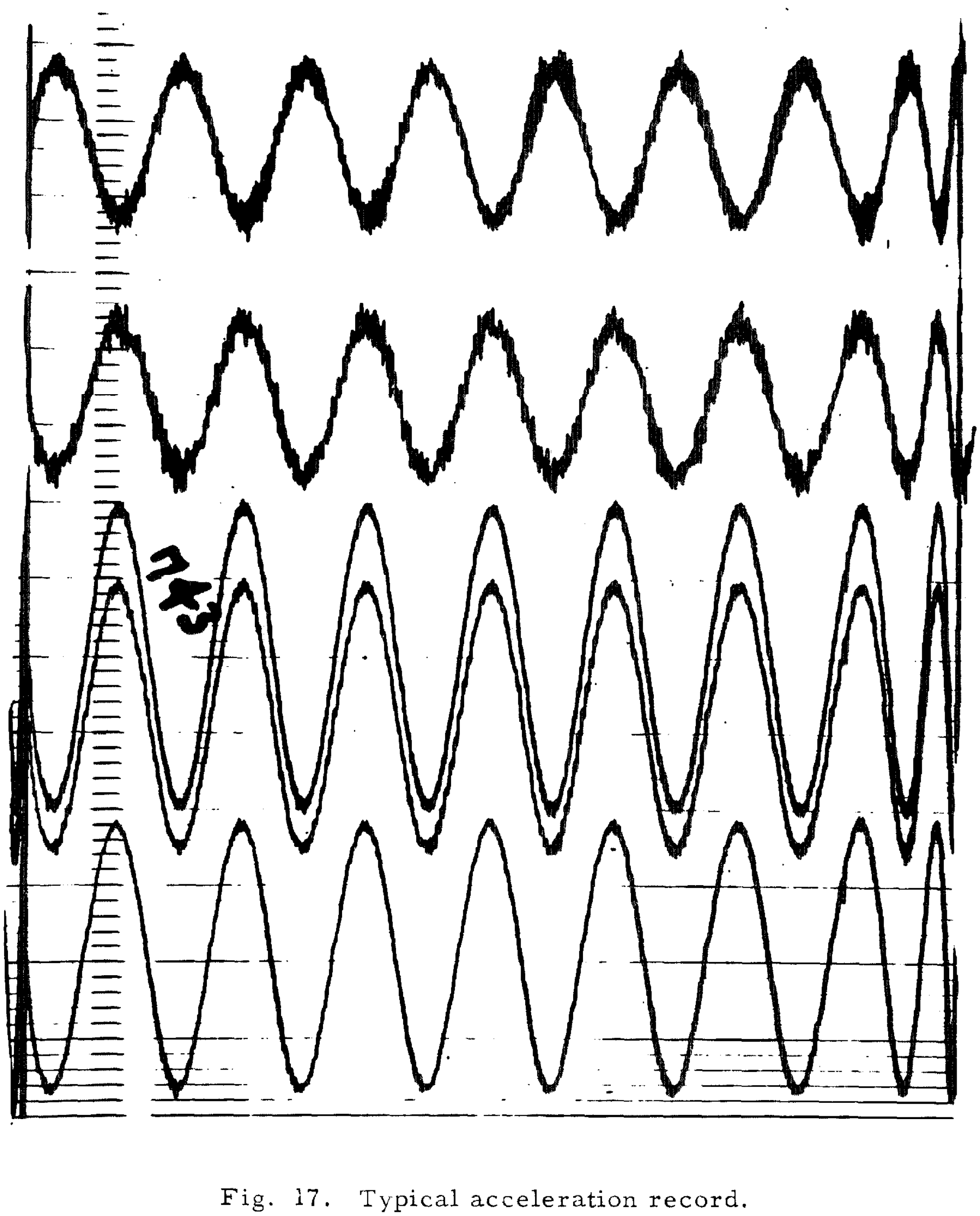


Fig. 17. Typical acceleration record.

sinusoidal force is not limited by the mounting position of the force generator. The weights for usual full-scale structural testing have been made of lead, but for the work reported here, steel weights have also been used.

The force amplitude generated is

$$\text{Inertia force (pounds)} = F_o = 0.102\ WRf^2$$

where W is the weight added to the baskets in pounds, R is the distance from the centroid of the weights to the axis of rotation in inches, and f is the excitation frequency in cps. Using only the small-size weight, the equation reduces to

$$F_o = Bf^2$$

where

$$B = 1.02W$$

because $R \approx 10$ inches. W is the total weight added to both baskets. The maximum value of $F_o$ is 5000 pounds per generator which is the limit based on the mechanical strength of the generators. The force generator was connected to the structure at the concrete slab level of the equipment room with the axis of the baskets located on the centerline of the gymnasium (Fig. 18).

The chain-drive system is driven by a 1-1/2 horsepower D. C. motor through a timing belt which has a 3:1 speed reduction. The drive motor and the tachometer assembly can be disconnected from the generator for easier handling, transportation and installation. A tachometer which gives 100 pulses per revolution was connected to the motor drive system.

The output of this tachometer (300 pulses per basket revolution) was monitored with a Berkeley Digital Counter. The stability of the system

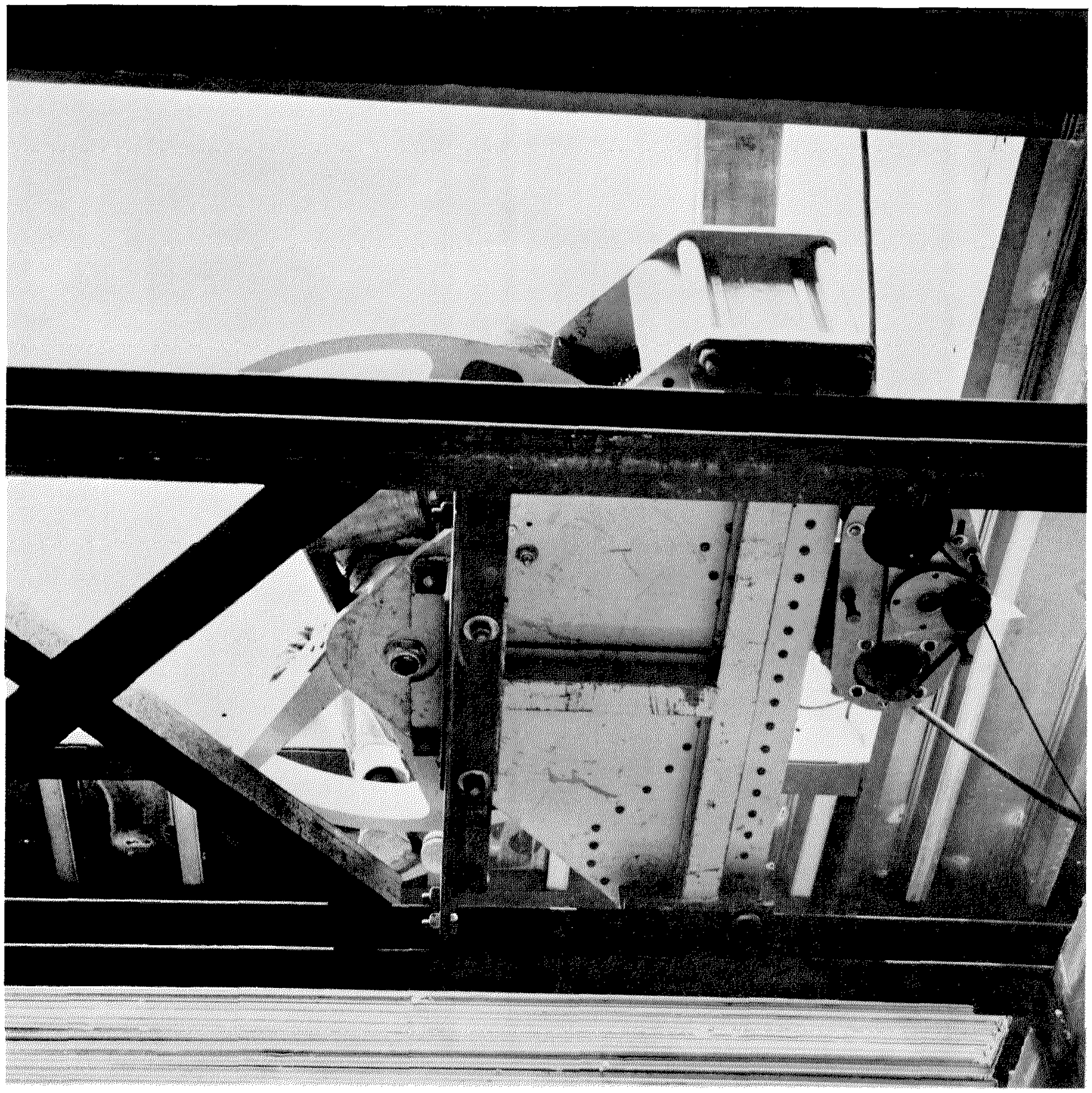


Figure 18. Force generator.

was such that the speed of the generator could be controlled to within ±1 count.

The source of the ambient high frequency signal was suspected to be the Broadway Power Plant of the Pasadena Light & Power Company which is located west of Blair High School just across the Pasadena Freeway. After completing the dynamic study, a check of the ambient accelerations was made using the 100 cps galvanometers. It was determined that the amplitude of the signal varied from time to time with peaks as large as five times the usual amplitudes.

The single amplitude acceleration results of this study are as follows:

| Location | Horizontal | Vertical | Comment |
|---|---|---|---|
| On ground at center of Power Plant | 0.00072 | 0.0050 | 60 cps only (Fig. 19) |
| On ground at south edge of Power Plant | 0.0002 | 0.00028 | 30, 60, 100 |
| On ground east of Blair Gymnasium | 0.00027 | 0.00011 | " |
| At lower level of equipment room | 0.00131 | 0.00318 | " |
| At concrete level of equipment room | 0.0002 | 0.00103 | (See Figs. 16 and 17) |
| At upper level of equipment room | 0.00148 | 0.00486 | " |
| Four feet below ridge peak at 20 | 0.0030 | 0.0041 | " |

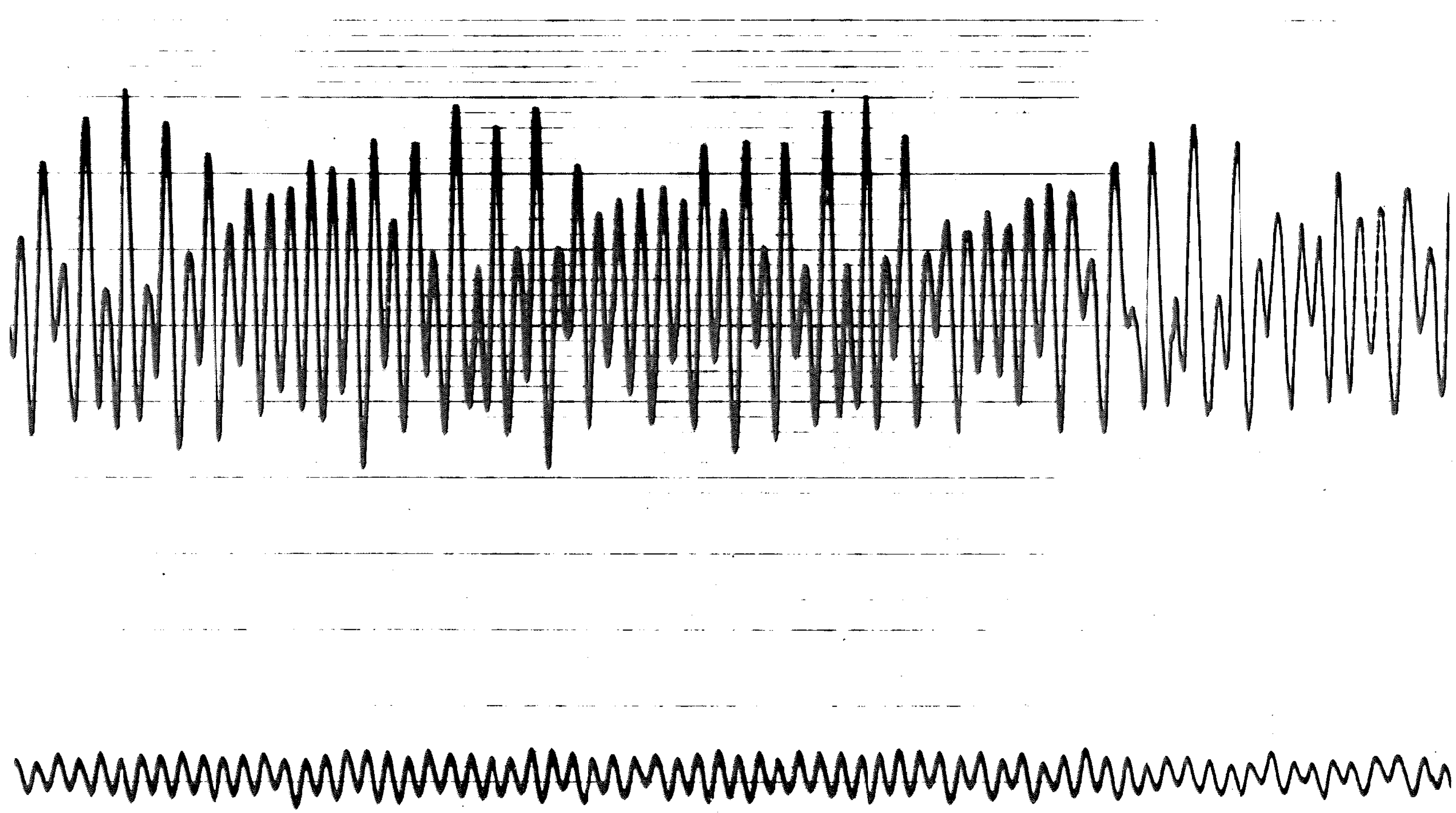


Fig. 19. Ambient acceleration.

The data obtained in the forced vibration studies contained this ambient acceleration because the 40 cps galvanometer was not very effective in filtering a 60 cps signal. The higher frequency signal was averaged out of the data by eye without excessive difficulty in most cases. In the following figures the single amplitude embient acceleration contained in the data is indicated by the vertical line "I". It should be noted that this does not indicate an error (see Figs. 16 and 17).

The symbols N, S, E, or W in the following figures identify the accelerometer locations as being one foot from the North, South, East or West edge of the equipment room concrete slab on an axis of symmetry. Figure 1 shows these locations and that the North truss crosses the equipment room from ⟨3⟩ to ⟨21⟩.

Results of Dynamic Tests

Figures 20 and 21 show the frequency response of the gymnasium to excitation in the North-South direction. It should be noted that the response associated with lower natural frequency is a combination of horizontal and vertical motion and that the higher natural frequency mode is predominantly vertical motion at the ends of the equipment room. The vertical motion at the south end was 180 degrees out of phase with the vertical motion at the north end in all tests. The damping calculated by the band width at the half power point of curve (4), Fig. 20, is 1.03 per cent of critical. Figure 22 gives the horizontal response in the East-West direction and Fig. 23 gives both vertical and horizontal response in the East-West direction. The vertical motion at the East and West positions also were 180 degrees out of phase for all tests. The damping calculated by the band width at the half power point of curves (3), Fig. 22, is 1.32 per cent of critical. Figure 24 compares the response curves at the same force levels at various days throughout the testing sequence. It should be noted that weight of the structure did not change appreciably from 25 June until the dynamic studies were completed. The material to be included in the weight of the structure for the dynamic tests are: the steel of the structural system, three fans located at the lower level of the equipment room, the aluminum access stairway to the equipment room, the roof insulation stored in bundles, the sheet rock for the partition walls in the equipment room, and the lathing frame for the parapet wall.

Response at the exterior edge of the structure was not obtained because the ambient acceleration was fifteen times that on the concrete slab in the horizontal direction. Since the existence of the ambient signal was not known until after the forced dynamic studies had begun, there was not sufficient time to establish an alternate recording system to filter the ambient acceleration.

The basic mode shape for the structure in the North-South and East-West directions is given in Fig. 25. Only the proportion of the vertical and horizontal components change for the various natural frequencies. The steel stairway was supported on small metal tubes at the bottom during the dynamic studies to prevent a horizontal force existing at this position. However, the nonsymmetry of the stairway relative to the structure was expected to cause a nonsymmetrical response of the structure. This was observed by comparing the response of the N and S vertical accelerations.

Figure 26 shows the oscillogram of a test in which the frequency was constantly decreased from 7 cps to 0 cps with excitation in the

the North-South direction and B = 43.45 . The data channels from left to right are: W horizontal, E horizontal, S vertical, N vertical, and North Truss horizontal. Note the beats and the differences between horizontal and vertical accelerations at various excitation frequencies.

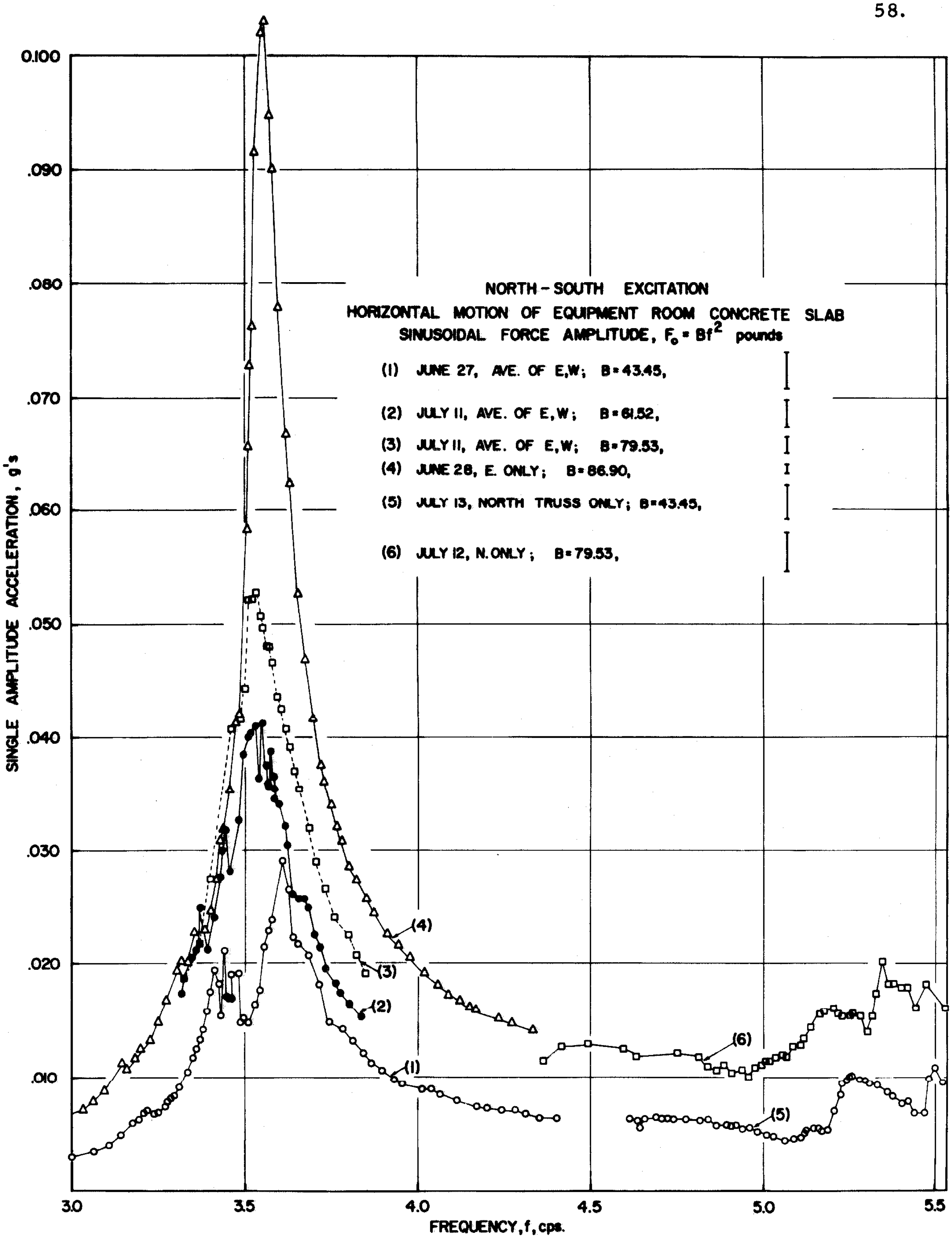



Fig. 20. Frequency response of gymnasium.

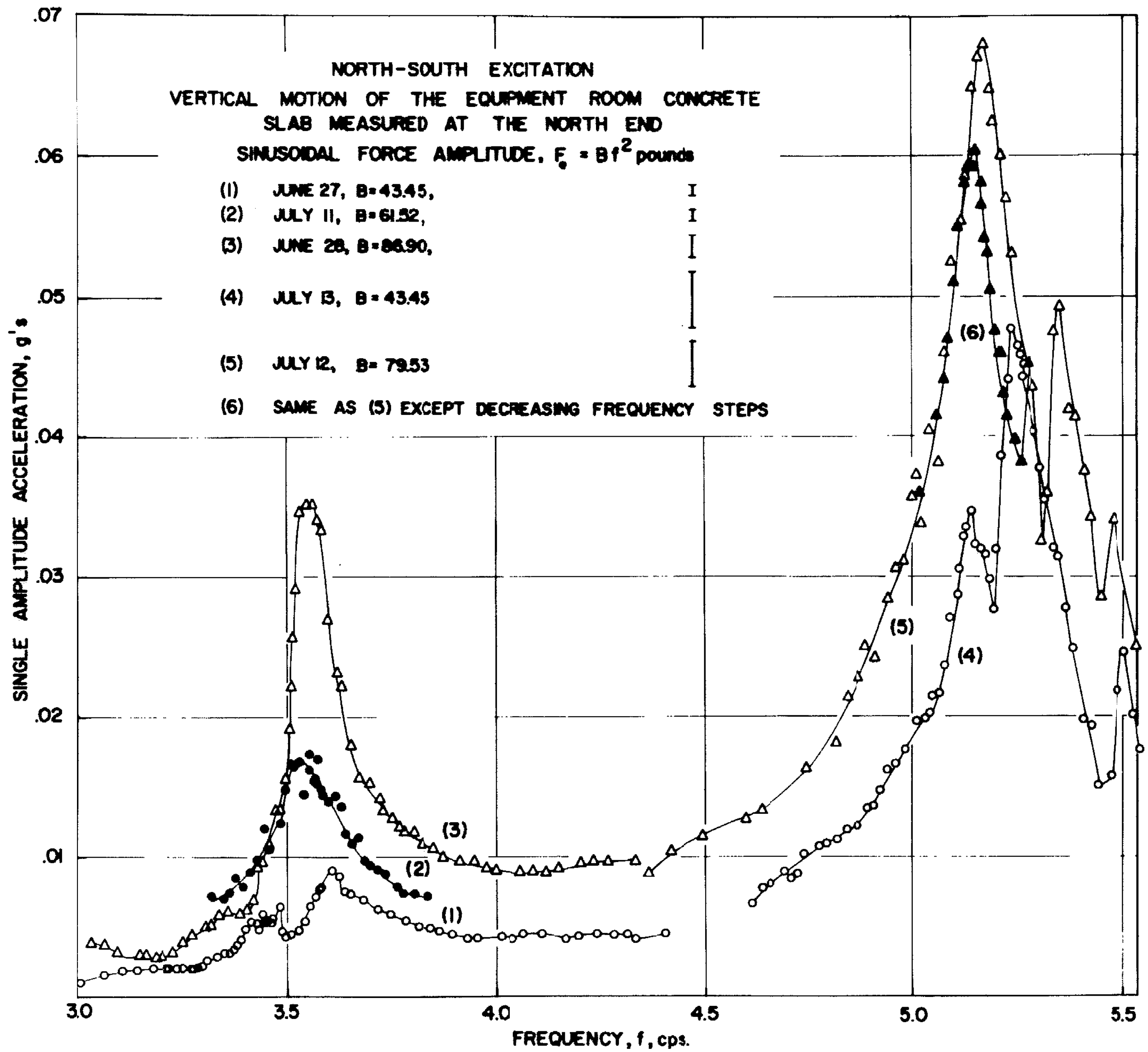



Fig. 21. Frequency response of gymnasium.

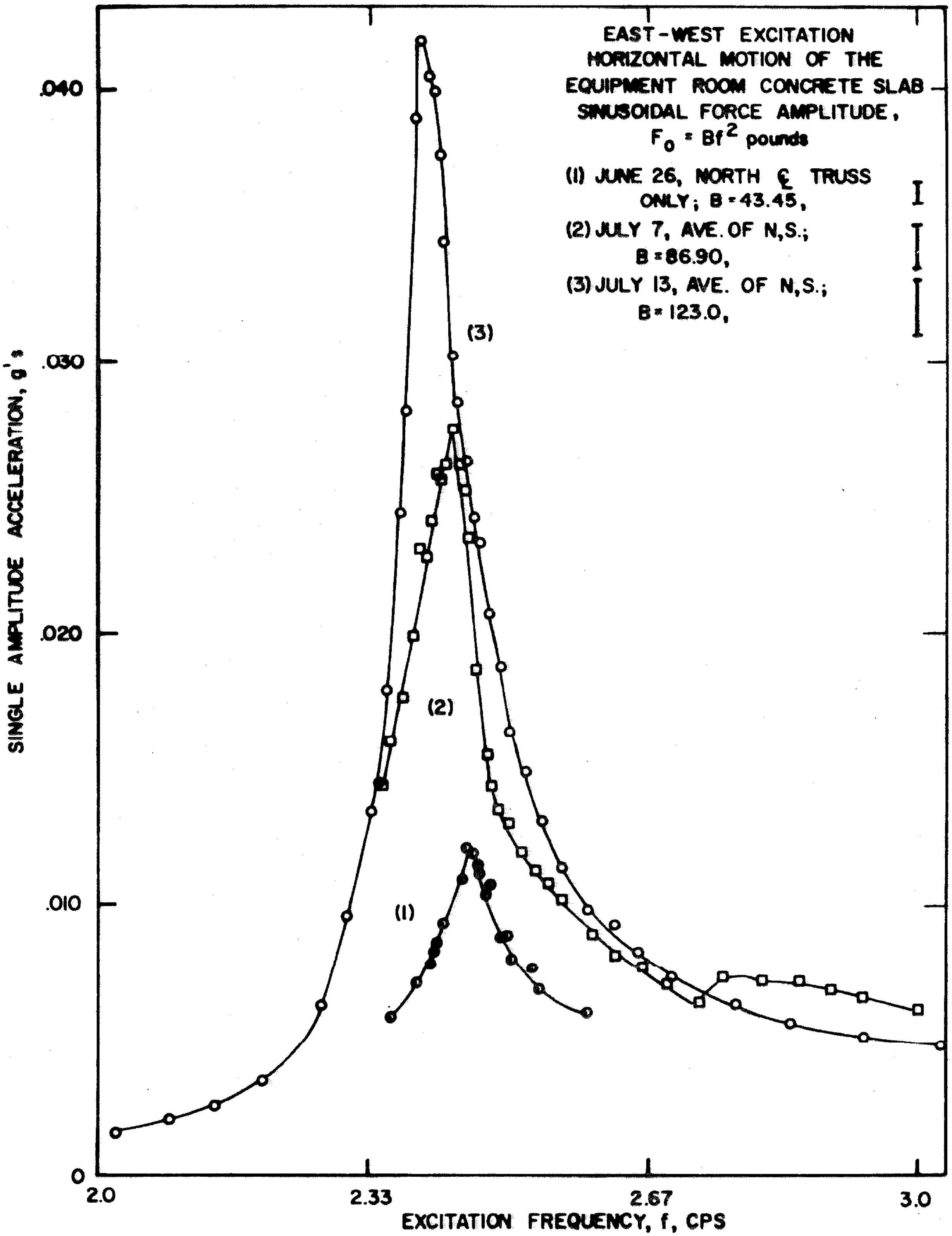



Fig. 22. Frequency response of gymnasium.

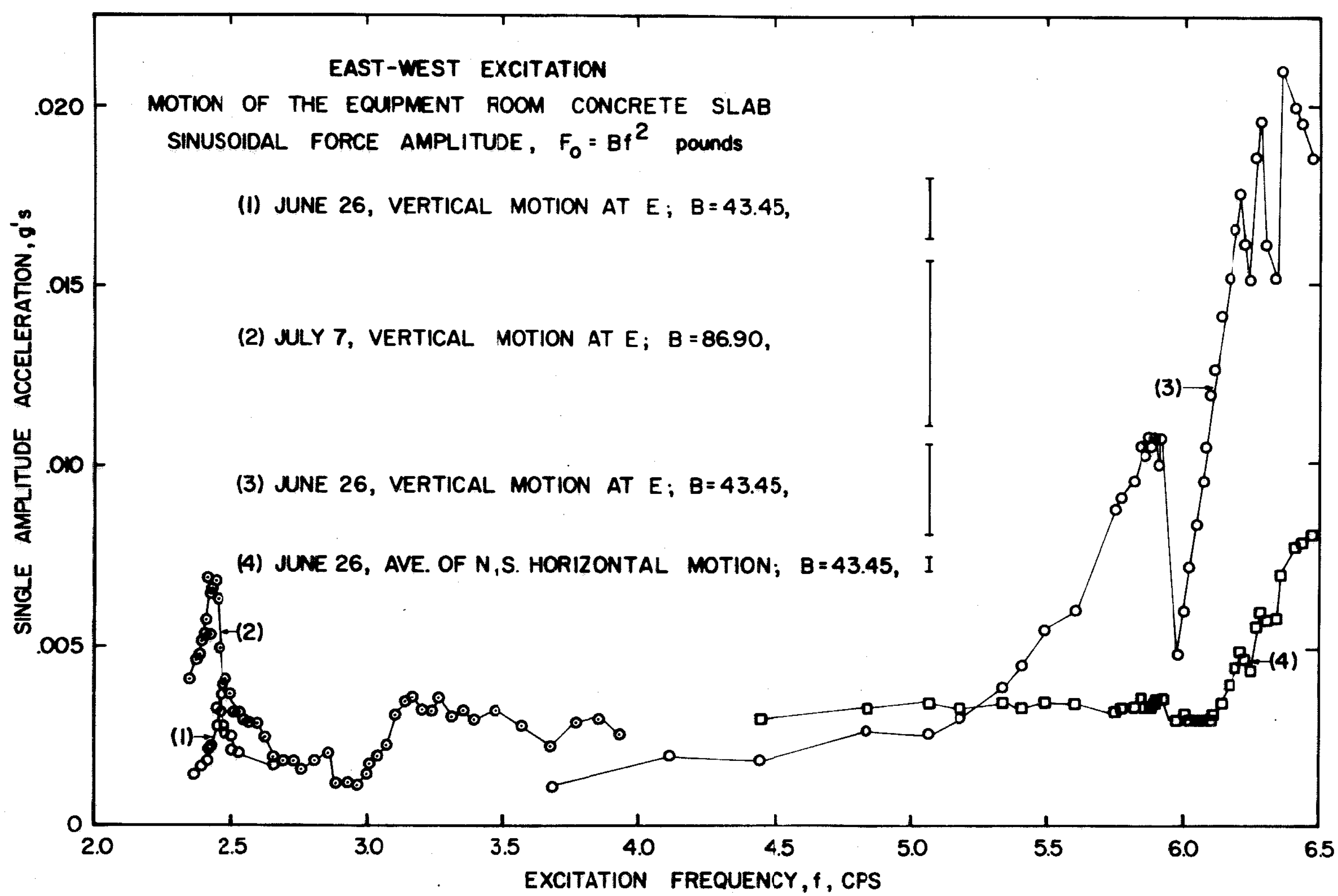



Fig. 23. Frequency response of gymnasium.

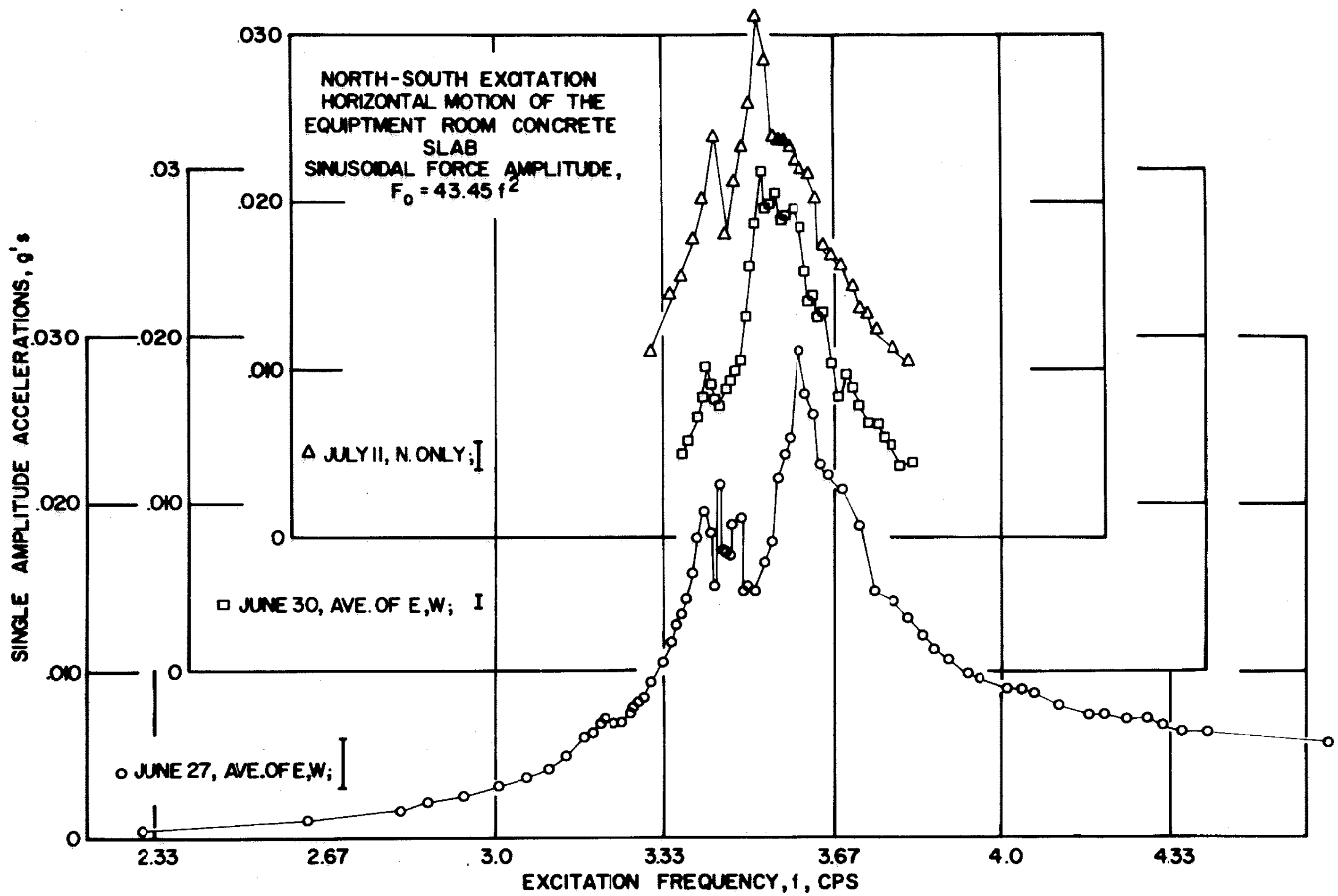



Fig. 24. Frequency response of gymnasium.

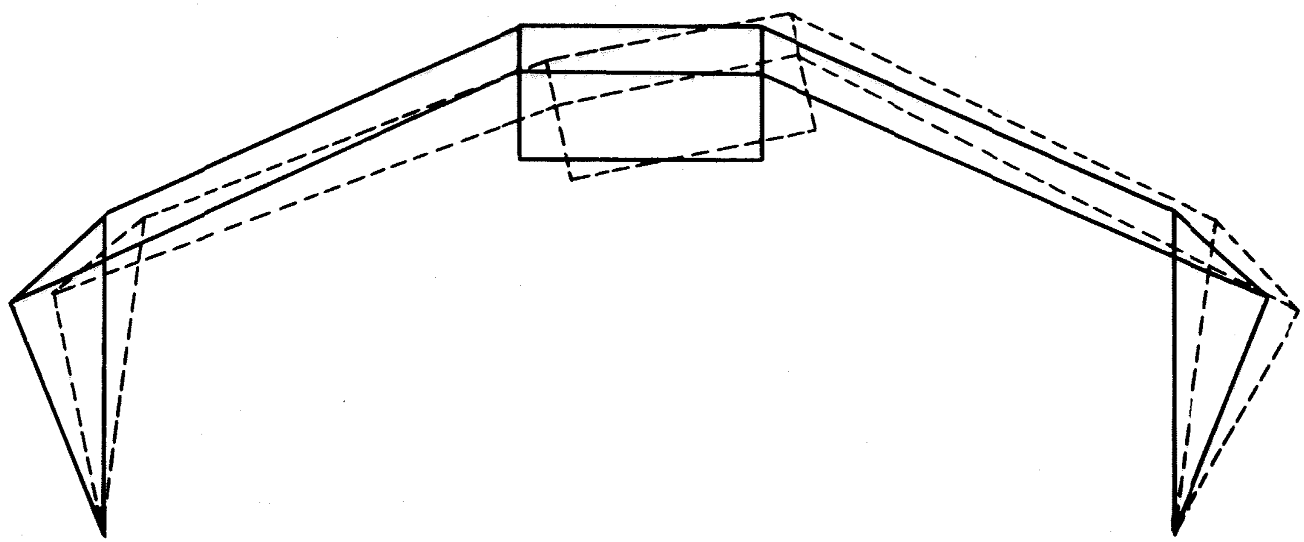


Fig. 25. Basic mode shape of structure.

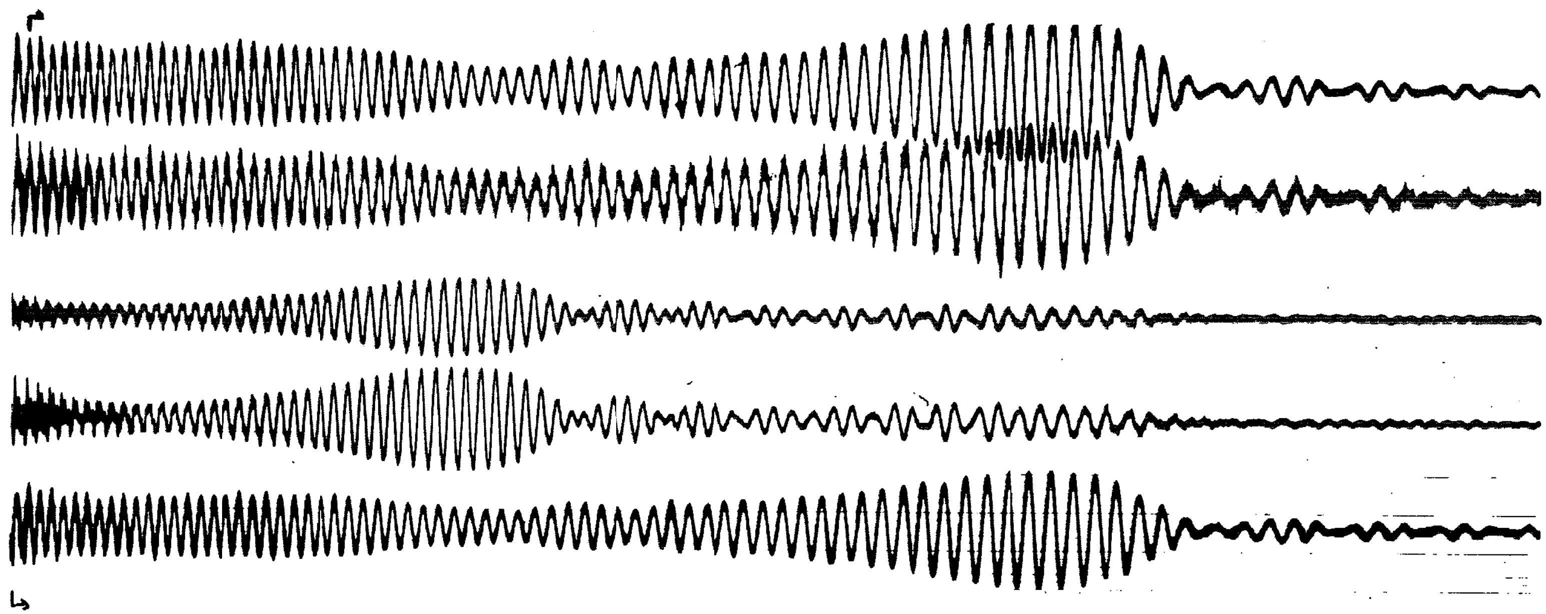


Fig. 26. Response to decreasing frequency.